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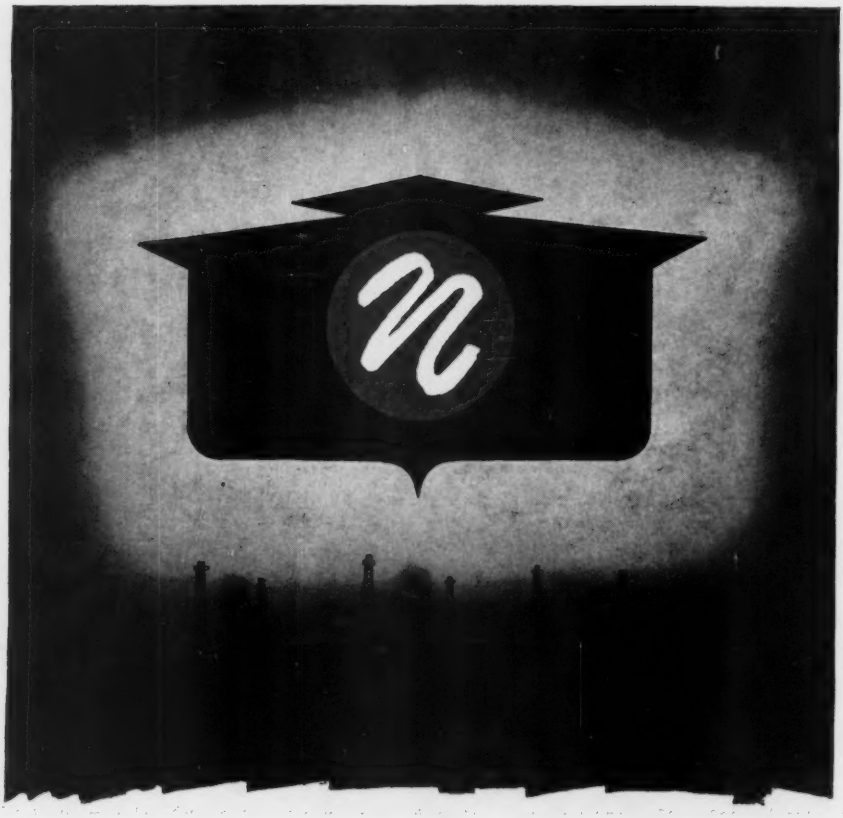

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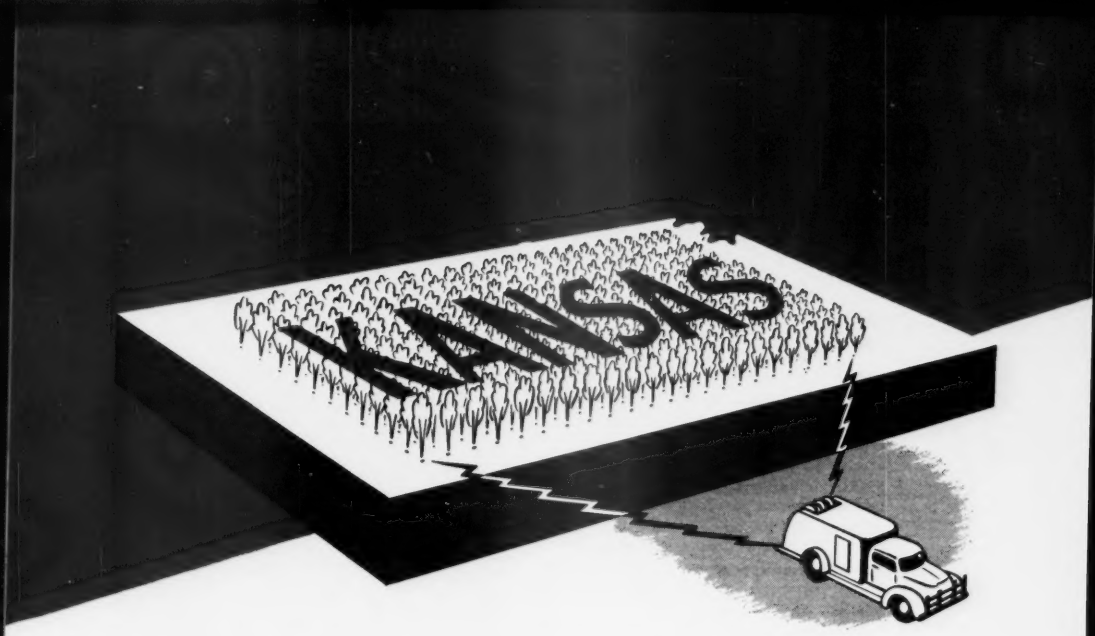

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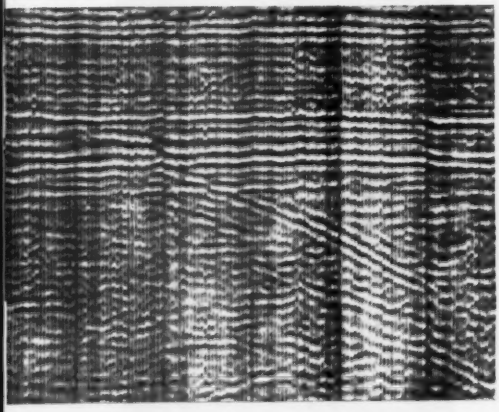

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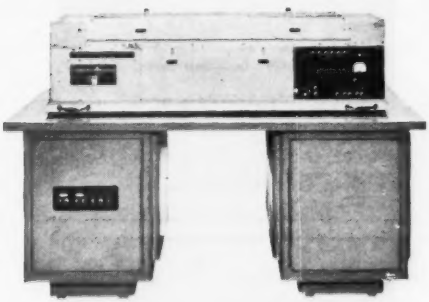

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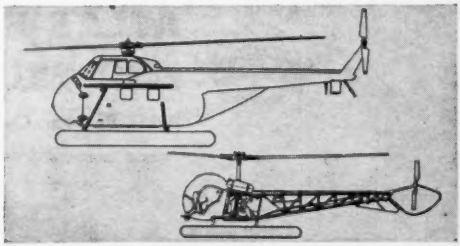

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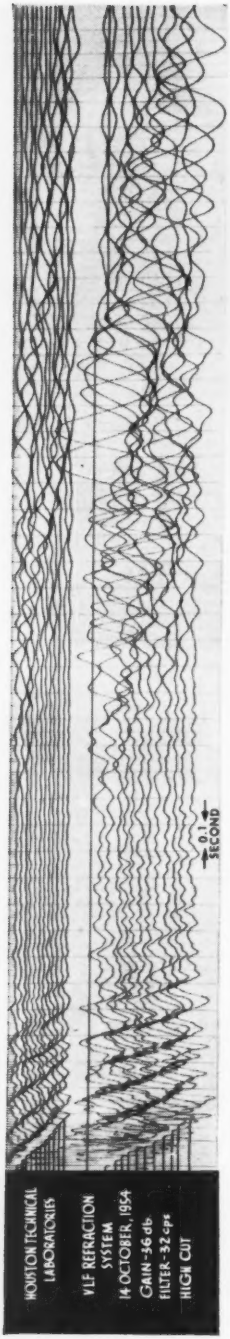

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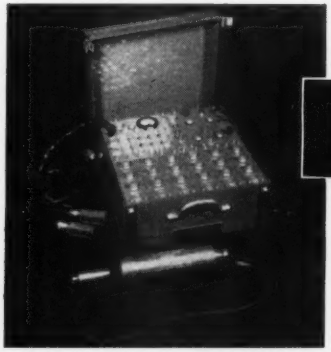

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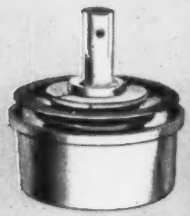

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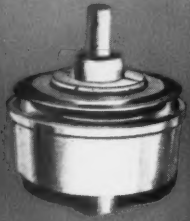

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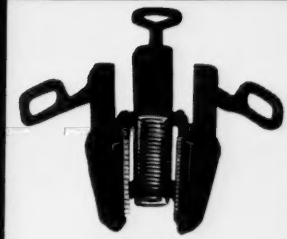

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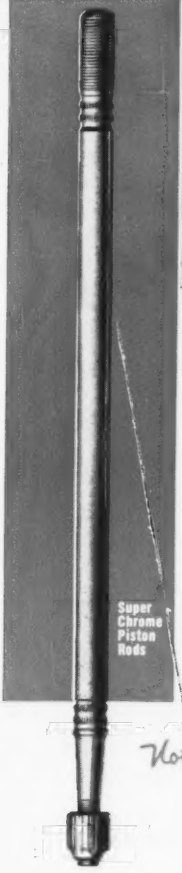

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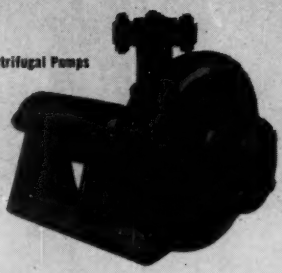

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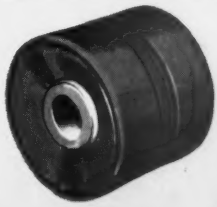

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VOLUME XXI OCTOBER, 1956 NUMBER 4

GEOPHYSICS

INVESTIGATION OF SHEAR WAVES*

R. N. JOLLY†

ABSTRACT

A series of measurements was made to investigate some of the fundamental properties of shear waves and to explore the possibility of using horizontally polarized (SH) shear waves for reflection prospecting. A special source was devised to produce a shearing motion which was detectable as far as 400 feet vertically and 1,000 feet horizontally. Direct, refracted, and reflected SH and SV (vertically polarized) shear waves were identified on a series of surface and subsurface recordings. A strong, highly dispersive surface wave, which satisfies the theoretical criteria of Love waves, was also observed.

Certain anomalous features of the data which did not conform to the predictions of simple isotropic theory were readily explained by considering the stratified section under observation to be transversely isotropic. It was found that horizontal SH velocity exceeded vertical SH velocity by 100 percent whereas the corresponding compressional wave velocities differed by only 12 percent. SV anisotropy was manifested by a complex variation of velocity at intermediate directions of travel. Other theoretical predictions were confirmed in detail by the experimental data.

An evaluation of SH reflection recording was made in four different areas. It was possible at one location, using multiple horizontal geophones and the shear source, to obtain an SH reflection from the base of a thick weathered layer. However, the results in general indicate that the method is not likely to have much practical importance.

INTRODUCTION

Current seismic exploration techniques all utilize the compressional type of elastic wave. However, in the past a considerable amount of research has been carried out to determine the properties of other wave types. The bulk of the material reported in the literature is concerned with surface waves, which cannot be used for geophysical exploration at depths of geologic interest. Reported research on body-type shear waves, which might be used for subsurface exploration, is meager.

In the period 1938–40, research personnel of The Carter Oil Company investigated the possibility of obtaining shear wave reflections using sources such as shallow-hole shots, sledge-hammer blows on stakes and on the walls of pits, weights sliding down inclined planes, etc. Although the results obtained were negative insofar as direct shear wave reflections were concerned, they did lead to the composite reflection technique, reported by Ricker and Lynn (1950). This method is based on the recording of shear reflections produced by the conversion of incident compressional pulses.

* Manuscript received by the Editor May 23, 1956.

† The Carter Oil Company, Research Department, Tulsa, Oklahoma.

More recently, interest has been expressed in the possibility of recording direct shear reflections of the SH type. Such waves, which are horizontally polarized, theoretically do not undergo change of type when they are reflected or refracted, as do longitudinal (P) waves or vertically polarized (SV) shear waves. It might therefore be expected that simpler seismograms would be obtained if SH waves could be used for reflection prospecting. Although this theoretical simplicity was a motivating factor behind the research to be described, a study of SH waves was attractive from a purely exploratory standpoint, since practically no data of an experimental nature were available for such waves.

An investigation was initiated whose principal objective was the experimental study of some of the properties of SH waves. A further objective, contingent on the outcome of the fact-finding phase, was to determine the applicability of SH waves to reflection prospecting. A limited study of SV waves was undertaken to attain a more complete understanding of shear waves in general, and a few compressional waves measurements were made for the same purpose.

EXPERIMENTAL PROCEDURES

Locale

Fact-finding experiments were confined to a test site near Mounds, Oklahoma, where there is a fairly thick, uniform section of shale near the surface. The area immediately surrounding the test site is flat and free of surface irregularities. Previous work indicated that the weathered layer is thin and that the velocity in this layer is relatively high. It was felt that uniform, competent surface layering would be most favorable for the generation and propagation of SH waves and at the same time unfavorable for the generation of interfering surface waves. Unfortunately, the scope of the experimental program was such that fundamental measurements could be made at this one test site only.

Reflection recording tests were carried out in four areas of Oklahoma having widely varying near-surface conditions. Data on weathered layer properties and shallow reflector depths were in most instances available from previous experimental shooting. The first reflection tests were made at the Mounds site, and subsequent reflection recording experiments were carried out near Burbank, Guymon, and Sand Springs, Oklahoma.

Equipment

A suitable generator of shear waves was an all-important prerequisite to the initiation of this investigation. The primary need was for a simple, low-power source which would provide SH or SV waves reasonably free of compressional energy. Some means of imparting an unbalanced horizontal force to the ground seemed most likely to achieve the desired results.

Sledge hammer blows against a vertical concrete slab set at the end of a trench served as the initial shear-wave source. It was found that a substantial amount of shear energy was generated, and refracted first arrivals could be de-

tected as far as 400 feet from the source. However, it was felt that insufficient amplitude was available from such a source to record with geophones at depth. Although amplitude could be increased considerably by the use of a large swinging weight, for example, such a device would be very unwieldy for field use. Consequently a more flexible source was sought.

The recoil device illustrated in Figure 1 was found to have the desired characteristics and was used extensively during this investigation. For obvious rea-

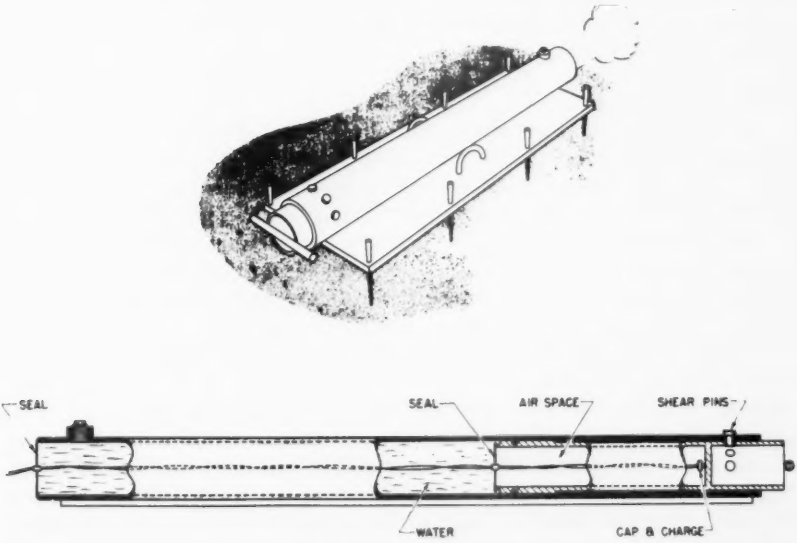

FIG. 1. Recoil device used to generate shear waves.

sons it was often referred to as a "gun." It consisted essentially of a length of thick-walled steel tubing, closed at one end and welded to a horizontal base plate that could be coupled to the ground by steel pegs. Small charges of low-velocity dynamite were detonated near the closed (breech) end of the tube to provide a horizontal recoil. The tubing was partially filled with water to provide greater recoil thrust and to reduce the air blast. The breech was fastened in the barrel by shear pins and was removable to permit loading.

It was determined that about 20 grams of dynamite could be safely used in this device. Larger charges caused the shear pins to mar the inner surface of the barrel so that the breech had a tendency to stick. More than 150 shots were fired in the gun, and no major difficulties were experienced except on two occasions when the breech cracked and new ones had to be made.

Variable reluctance horizontal and vertical geophones having natural fre-

quencies of 4 cps were used for surface recording. Geophones of the dynamic type, having natural frequencies of 8 cps, were used for subsurface recording. These geophones were pushed firmly against the borehole wall by an expandable arm arrangement to insure good coupling with the surrounding formation. Calibrated, fixed-gain amplifiers with frequency response flat over the range 5 to 500 cps were used in conjunction with a standard recording camera.

Ordinary 17 cps dynamic geophones, modified for horizontal planting, were used in multiple for reflection recording. A set of conventional amplifiers, having AVC and filtering, were operated in parallel with the flat amplifiers to record reflection spreads.

Shooting Procedure

The fact-finding measurements undertaken at the Mounds test site may be conveniently classified as either surface or subsurface. Surface measurements were made to investigate refracted waves and surface waves, and subsurface measurements were made to study the behavior of direct waves.

Surface shooting was carried out using a conventional refraction spread of geophones (vertical, horizontal, or both). Equipment limitations frequently required the use of several spread segments, with common end geophones, to achieve the desired spread coverage.

The procedure used for subsurface recording can best be understood by reference to Figure 2, which is a schematic representation of the instrument layout. Adjacent vertical and two-component horizontal geophones were locked in at each of three vertical stations in the instrument hole, and three horizontal geophones with movements parallel to the recoil device were placed on the surface as shown. The outputs from these geophones were recorded as the recoil device occupied successive positions outward in a straight line from the instrument hole. This shooting procedure is similar in principle to that used by Ricker (1953) in his fundamental study of compressional waves.

Such a series of measurements provided direct wave ray paths between the source and the subsurface geophones, which ranged from essentially vertical to near-horizontal. Measurements of direct waves traveling along these paths provided data from which three time-distance curves could be constructed. In turn, the shapes of the wave surfaces could be inferred from the time-distance curves. The surface geophones were useful for studying the behavior of refracted and surface waves simultaneously with that of direct waves.

Most reflection profiles were laid out in the usual manner, and the recoil device was used as the source for SH waves. Sixteen horizontal geophones per trace were required to compensate for inadequate source strength and to attenuate interferences. The lack of a sufficient number of horizontal geophones at the onset of the experimental program required the use of a single trace of geophones and multiple positions of the gun to secure a reflection profile. Later, as more geophones baceme available, it was possible to record six traces from a single

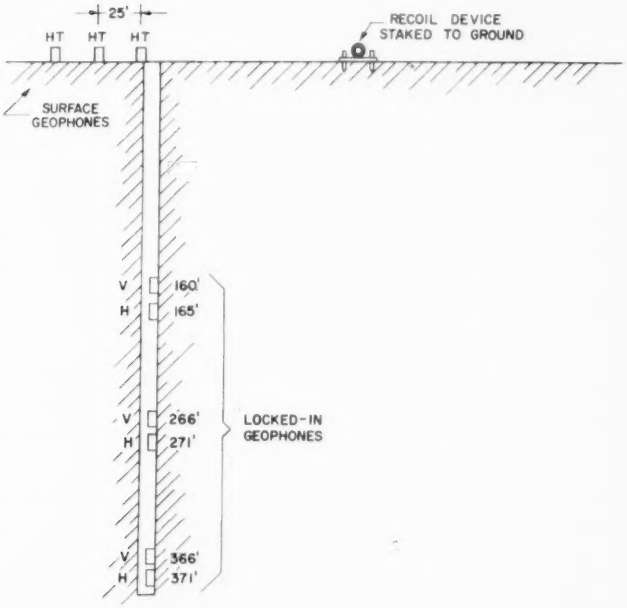

FIG. 2. Instrument layout for subsurface study of shear waves.

shot. Geophone movements were oriented at right angles to the profile and parallel to the source.

A number of variations in recording technique were used. Multiple geophone trace coverages ranged from 30 to 200 feet and shot-to-detector distances were as great as 500 feet. Trace overlap in some cases amounted to 70 percent. Mixing and a large variety of filtering were tried in an effort to arrive at optimum recording techniques.

WAVE TYPES OBSERVED IN FUNDAMENTAL STUDIES

Predictions of Simple Theory

It is well known that two classes of body-type waves can propagate in an isotropic elastic medium. The compressional or P wave has the higher velocity and is characterized by in-line particle motion. The shear wave, because of its property of polarization, can be further subdivided into the SH and SV types, both of which have transverse particle motion and travel with the same velocity. They differ only in their direction of particle motion. The SH wave vibrates in a direction that is always horizontal and normal to the ray path. The SV motion, also normal to the ray path, lies in the plane of incidence, which is the vertical plane containing the source and detector if the layering is horizontal.

Surface, refracted, and reflected waves arise from body-type waves in the presence of layering. Surface waves, which are strongly attenuated with depth and which which travel more slowly than other waves, are usually of the Rayleigh or Love variety. The Rayleigh wave has a combination P-SV type of particle motion, and the Love wave has exclusively SH motion. The velocities of both these waves are usually frequency-dependent, and they are said to be dispersive.

Some of the criteria useful for the identification of wave types are these: (1) nature of particle motion, (2) polarizability by the source, (3) dispersive properties, and (4) velocity or conformance to theoretical time-distance curves. The first three criteria, of a qualitative nature, are used in the following discussion of experimentally observed wave types.

Waves Observed on the Surface

A number of refraction-type records were taken to see what wave types could be observed at the surface when a shear-wave source was used. Initial tests using the sledge hammer source and later tests of the same nature made with the recoil device gave almost identical results.

A sequence of the records obtained is shown in Figure 3. The application of shearing force was normal to the direction of the profile. All three components of motion were measured on record 1. The symbol "HT" refers to a horizontal geophone whose movement is normal to the profile, "HR" to a horizontal geophone whose movement is in line with the profile, and "V" to a vertical geophone. The first arrivals on the HT traces, tentatively identified as refracted (or direct) SH waves, are followed by high amplitude surface waves. Since the HR trace responds to P, SV, and Rayleigh-type waves, it is not possible at this point to identify with any certainty the events following the low-amplitude P wave on the HR trace. Later detailed measurements proved that the event marked SV is actually the refracted SV first arrival. The first events on the V traces of this record are ordinary refracted P waves, which are weak relative to the SH first arrivals on the HT traces. No compressional (P) energy is observable on the HT traces. Records 2 and 3 were made at greater spread distances using transverse horizontal geophones only. Record 4 differs from record 3 only in that lower amplifier gains were used to display the strong surface wave, which is well developed at this spread distance.

A more conclusive identification of the primary events on transverse horizontal traces as SH waves is provided by the records of Figure 4. Advantage is taken of the fact that the SH wave can be expected to change polarity when the transverse source is rotated 180 degrees. That this actually happens is seen by an inspection of event *a* on the two records. Compressional events *b*, *c*, and *d* on the vertical traces do not change polarity.

A more detailed study of the SV refracted wave can be made by reference to the records of Figure 5. SV event *e* reverses polarity as expected when the *in-line* source is rotated 180 degrees. No identifiable SH energy is recorded on

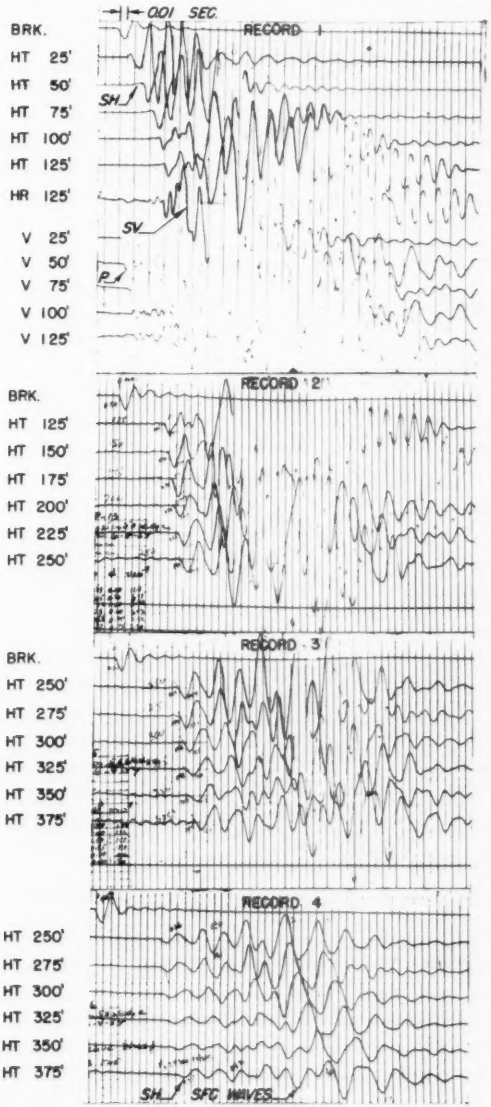

FIG. 3. Waves from transverse shear wave source as observed at the surface.

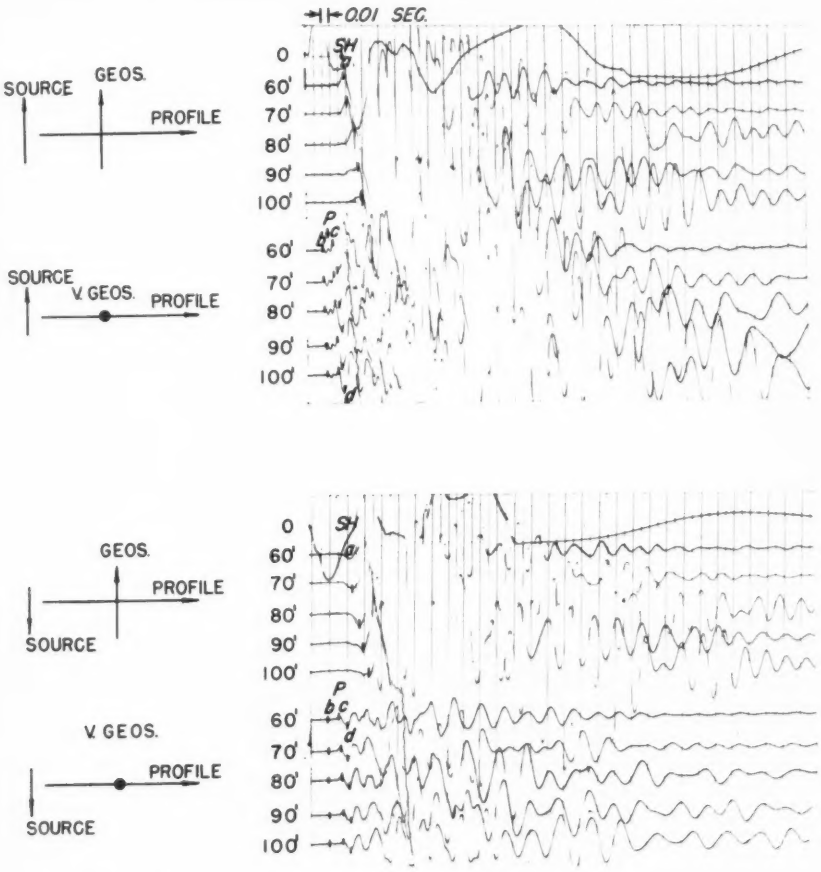

FIG. 4. Effect of 180 degree rotation of *transverse* source on polarities of primary surface events.

the transverse traces with this source orientation. As before, the compressional event *c* remains unchanged.

The records of Figure 6 were taken to examine the Love wave in some detail. The top record, made at a relatively short spread distance, shows on the upper transverse traces a series of well-defined, high-amplitude events with relatively large step-out following the refracted first arrivals. The Rayleigh-like wave on the lower set of vertical traces bears no apparent relation to the Love wave on the upper horizontal traces. The Love wave is much better developed at the longer spread distances of the bottom record. Only horizontal geophones were

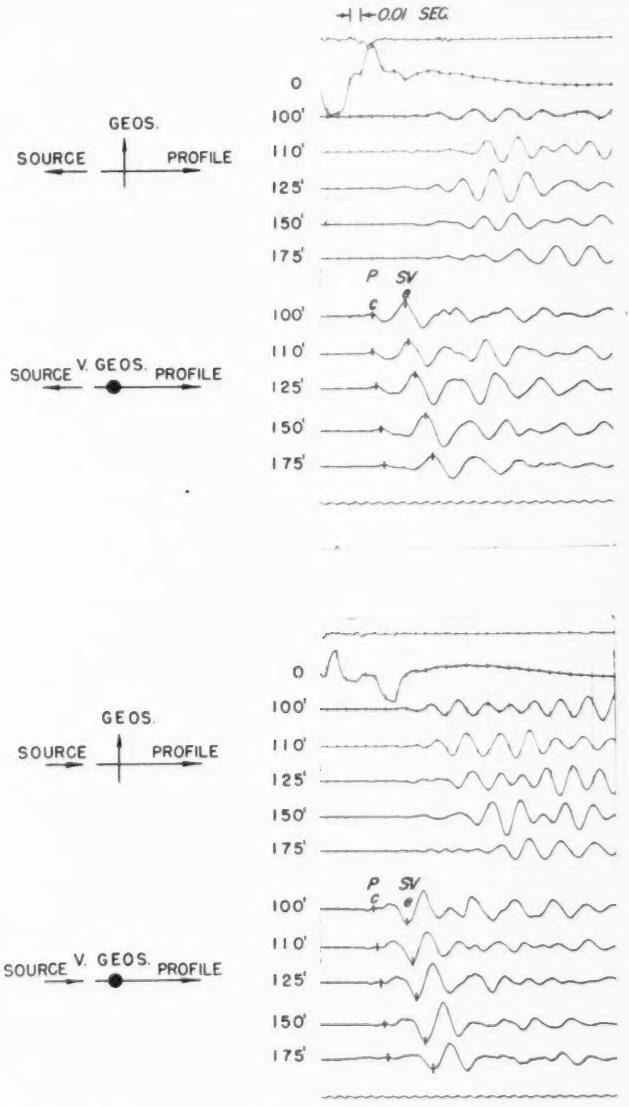

FIG. 5. Effect of 180 degree rotation of *in-line* source on polarities of primary surface events.

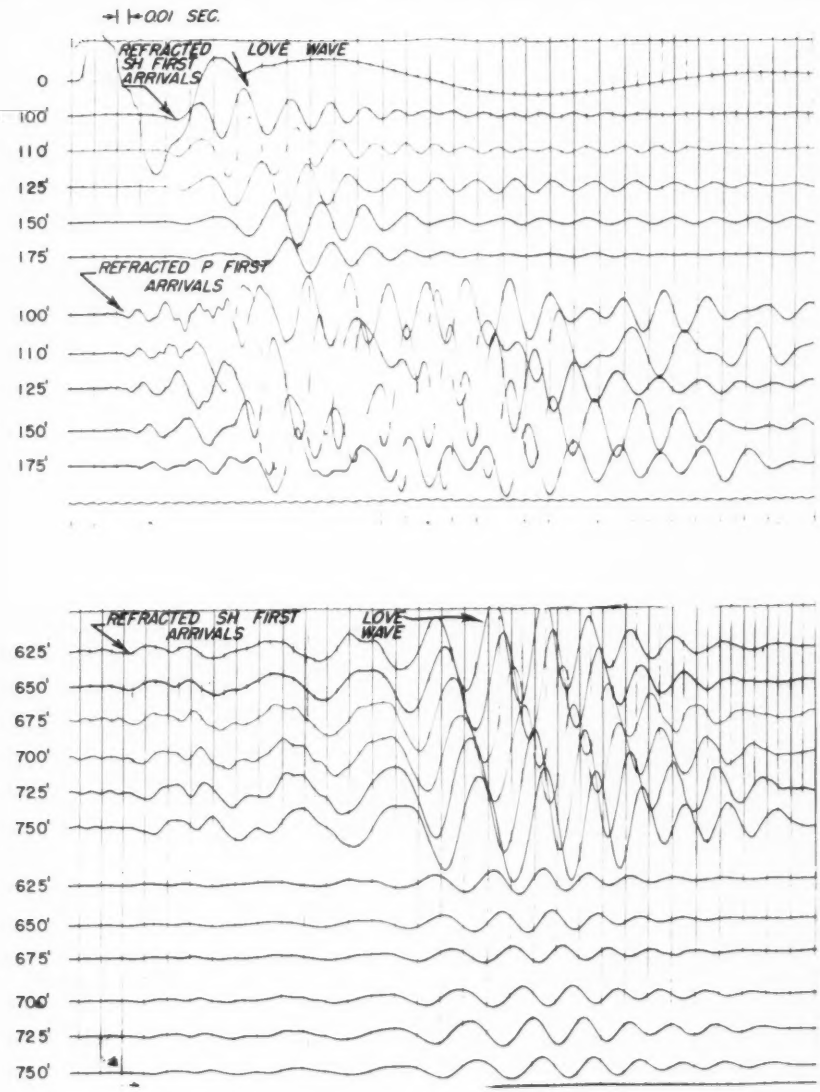

FIG. 6. Love waves observed on transverse horizontal geophones.

used in this instance, the lower set of traces being identical to the upper except for lower gain. The weak first arrivals are followed by a disturbance whose fundamental frequency increases with record time until a well-defined amplitude peak is reached. Superimposed on the low frequency component and following the refracted first arrivals are higher frequencies which may represent higher modes. These events are probably not secondary refractions because their step-out appears to be equal to or greater than that of the primary refraction.

Waves Observed at Depth

A general idea of the wave types recorded from locked-in subsurface geophones may be gained by reference to Figure 7. These records were made with the recoil device normal to the line connecting the instrument hole with the source location.

The horizontal component traces were arbitrarily polarized so that all kicked in the same direction. The first valley of the principal event on these horizontal traces, labeled S_1, proved to be the direct SH wave. The wave preserves its form fairly well as it travels downward, and the two horizontal components are approximately in phase at each depth. The unequal amplitudes of the two components may be attributed to their orientation, if it is assumed that the source is generating a strongly polarized wave. The event marked P is the direct compressional wave, to which horizontal component geophones would be somewhat sensitive since the compressional wave has a component of horizontal particle motion, particularly for the lower record. The polarities of these geophones for compressional disturbances are not necessarily the same as for other types of waves; the relative polarities for all geophones indicated in Figure 7 were determined by a shallow shot.

The vertical component traces exhibit two primary compressional events P_1 and P_2. The first is thought to be generated by the explosion of the charge and the second by the later slow recoil of the gun. Such multiple first arrivals were also noted on the surface spreads. An additional event S_2 on the vertical component traces appears for large horizontal distances. It cannot be a component of the SH wave because of its markedly different step-out. Subsequent investigation showed this event to be the direct SV wave.

A more detailed view of the various wave types observed at depth is provided by the tracings of Figure 8. Each pair of traces shows the effect of rotating the transversely oriented source 180 degrees. Such a procedure greatly facilitated wave-type identification. The initial arrival is the direct compressional wave, which is detected by both horizontal and vertical subsurface geophones. Its polarity is unchanged when the gun direction is reversed. The following disturbance, recorded on the subsurface horizontal geophones only, is the SH wave. All major cycles of this event are reversed in polarity with reversal of gun direction. Following the compressional wave on the vertical geophone traces is the SV wave, which exhibits no definite phase reversal. The manner in which an SV

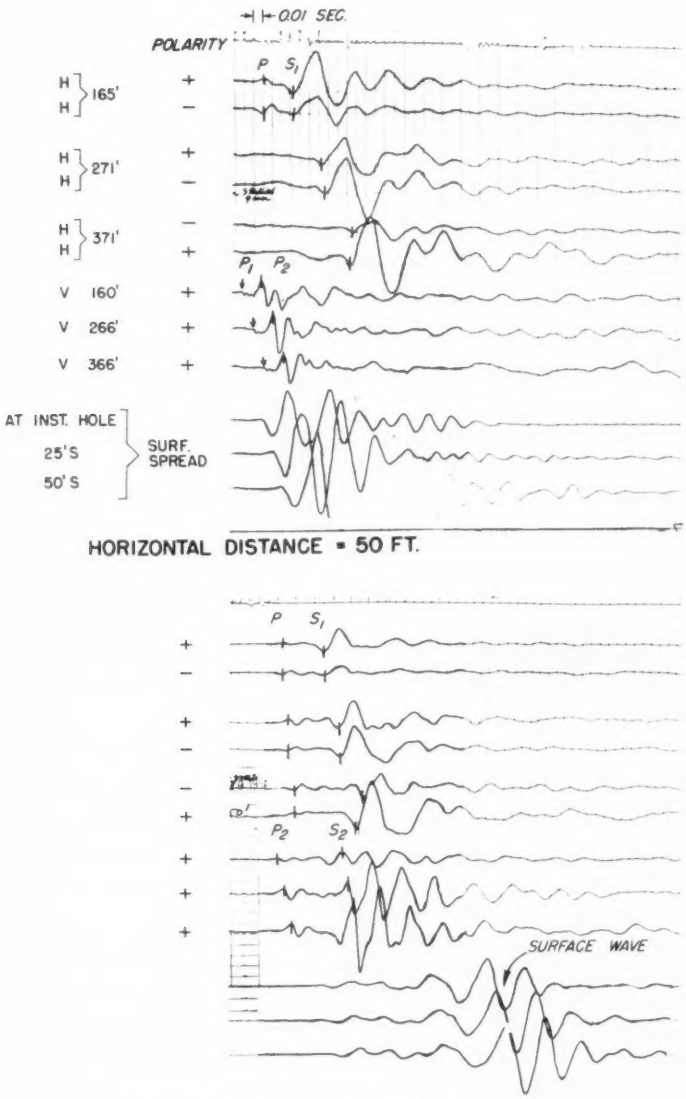

FIG. 7. Waves from transverse shear wave source as observed at depth and on the surface.

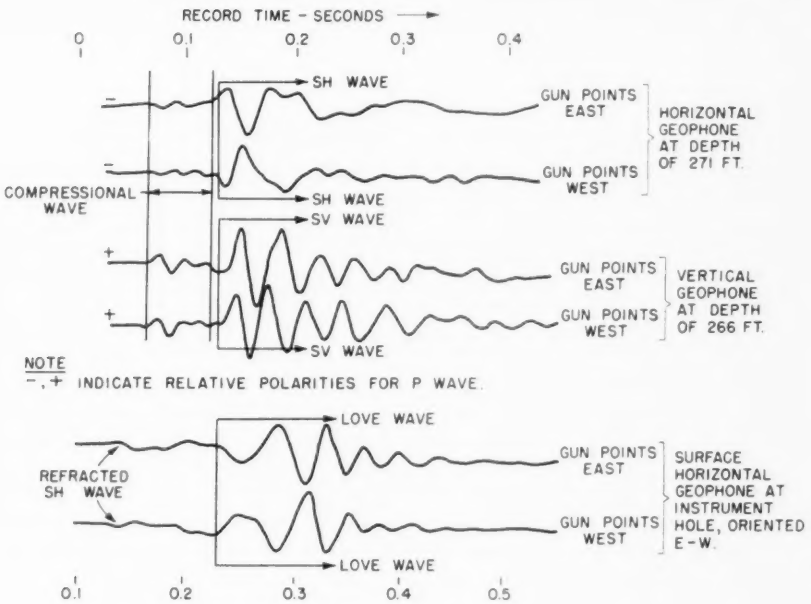

FIG. 8. Effect of 180 degree rotation of transverse source on polarities of events observed at depth and on the surface.

wave is generated by a transverse source is not immediately obvious; the fact that it is not polarized by the source suggests that it may result from P-wave conversion. The surface traces show the refracted SH wave and the Love wave, both of which change polarity with gun reversal.

The series of records presented in Figure 9 permit closer scrutiny of the direct SV wave generated by an *in-line* source and by shallow hole shots. The upper two records illustrate the behavior of the SV event when the source is reversed in direction. The expected reversal of SV polarity occurs. The presence of the SV wave on the horizontal traces may be attributed to the fact that the in-line source does not generate the SH wave which apparently masked out the SV wave in the preceding illustrations. Comparison of the vertical traces of the 350 foot records of Figures 7 and 9 indicates that the SV waves generated by the transverse and by the in-line source have similar waveform and step-out. Hence it is likely that these waves are fundamentally the same, in spite of the fact that one is source-polarized and the other is not.

The lower two records of Figure 9 illustrate the generation of SV waves by shallow-hole shots. The first of these records was taken at about the same horizontal distance as the upper two records to facilitate comparison of the SV waves

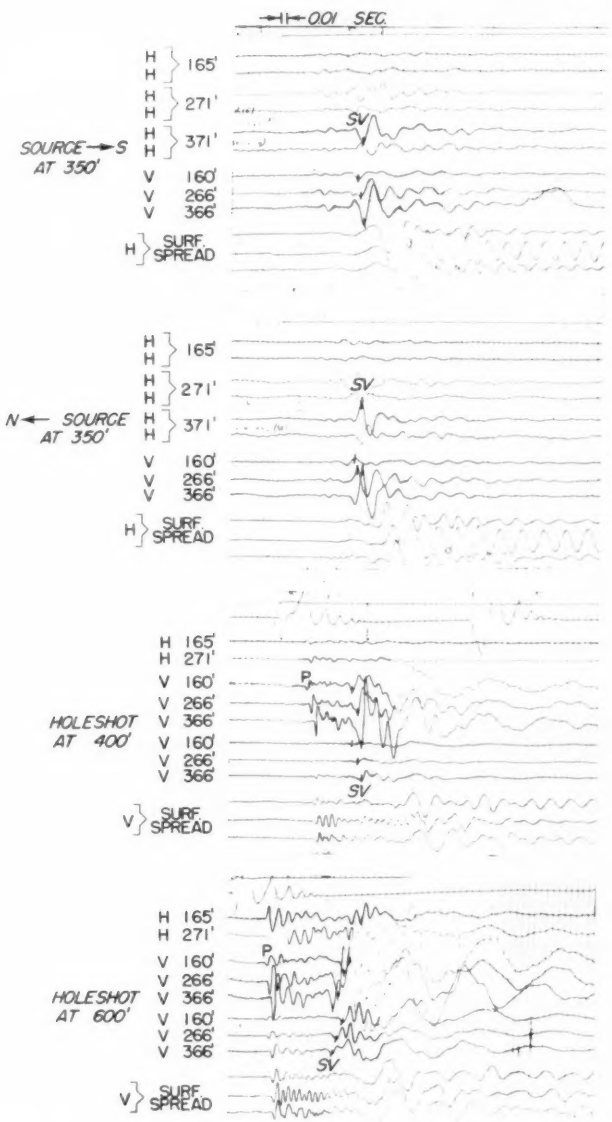

FIG. 9. SV waves from in-line shear source and shallow hole shots as observed at depth.

generated by the two types of sources. It is readily apparent from the step-outs that the waves are of the same general nature. As would be expected, the frequency content of the hole-shot SV wave is higher than that of the wave produced by the recoil device on the surface. Also the ratio of P-wave amplitude to SV-wave amplitude is much greater for the hole shot. Inspection of the lower record of Figure 9, taken at a greater horizontal distance, reveals that the SV wave has a *negative* step-out. This indicates that the wave is traveling upward and that its ray path is extremely curved. The systematic change of step-out from positive to zero to negative with increasing horizontal distance precludes the possibility that these events are reflections or refractions arriving from below.

ANALYSIS OF THE DATA

SH Wave

An SH refraction profile 1,000 feet long was shot using the recoil device as a source. The application of force was normal to the direction of the profile and parallel to the horizontal geophone movements. Records obtained were similar to those displayed in Figures 3 and 4.

The first 400 feet of the time-distance curve is shown in Figure 10, together with a magnified near-source waveform to illustrate the manner in which time picks were made. Due to the indistinct first arrivals, it was necessary to pick first peaks or valleys and estimate the time displacement of the first arrival curve.

The data points of Figure 10 fall reasonably well on straight line segments. The velocity breaks are well defined, and there is none of the curvature ordinarily associated with shear wave first arrival plots. An upper layer 3 feet thick with a velocity of 750 ft/sec and an intermediate layer 45 feet thick with a velocity of 1,600 ft/sec were calculated in the usual manner. The lower layer has a velocity of 4,850 ft/sec which appears to be constant for a spread distance out to 1,000 feet.

Subsurface recordings such as those of Figure 7 were made for horizontal distances ranging from 5 to 600 feet for the purpose of investigating quantitatively the behavior of the direct SH wave. Plotting of the arrival time of event S_1 (Figure 7) against horizontal distance from source to instrument hole, yields a time-distance curve (Figure 11) for each of the three geophone depths. Although there is considerable scatter of the data points, the shapes of these curves are well defined. Attempts were made to reconcile these data with theoretical curves computed using velocities and layering deduced from the previously described surface refraction profile. The theoretical curve shown in this figure for the 165-foot geophone was computed using the refraction profile velocity of 4,850 ft/sec, an LVL thickness of 19 feet, and a low velocity time of .025 second, determined from the refraction time-distance curve intercept. It is obvious that the shapes of the theoretical and experimental curves are entirely different and that the ordinary hyperbolic time-distance relation does not hold.

Interval velocities of 3,200 and 3,600 ft/sec for the upper and lower intervals,

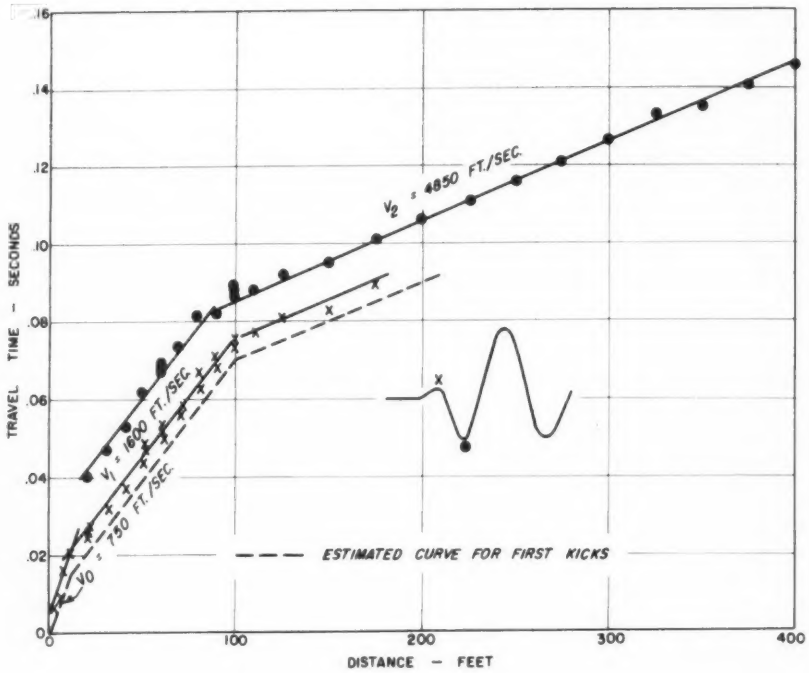

FIG. 10. SH refraction time-distance curve.

respectively, may be computed from near-vertical travel times. These vertical velocities, which were independent of the gun orientation, are much lower than the horizontal velocity determined by refraction. Attempts to fit theoretical curves computed using these velocities to the data points were likewise unsuccessful.

The directivity of SH waves generated by a sledge-hammer blow was investigated by recording SH profiles running in three different directions relative to the direction of the hammer blow. The horizontal geophone movements were kept normal to the profile. The directivity pattern inferred from these measurements is shown in Figure 12. In this polar diagram, the amplitude at any angle θ is proportional to the length of the radius vector r. Profiles were recorded in directions OA, OB, and OC, and relative amplitudes were determined for these different directions. Although points A, B, and C are the only data points, the assumption of symmetry allows other points to be plotted. Since it was suspected that the SH amplitude in the direction OC should be zero, a detailed study was made along a 30-degree arc centered about this direction. Amplitudes and

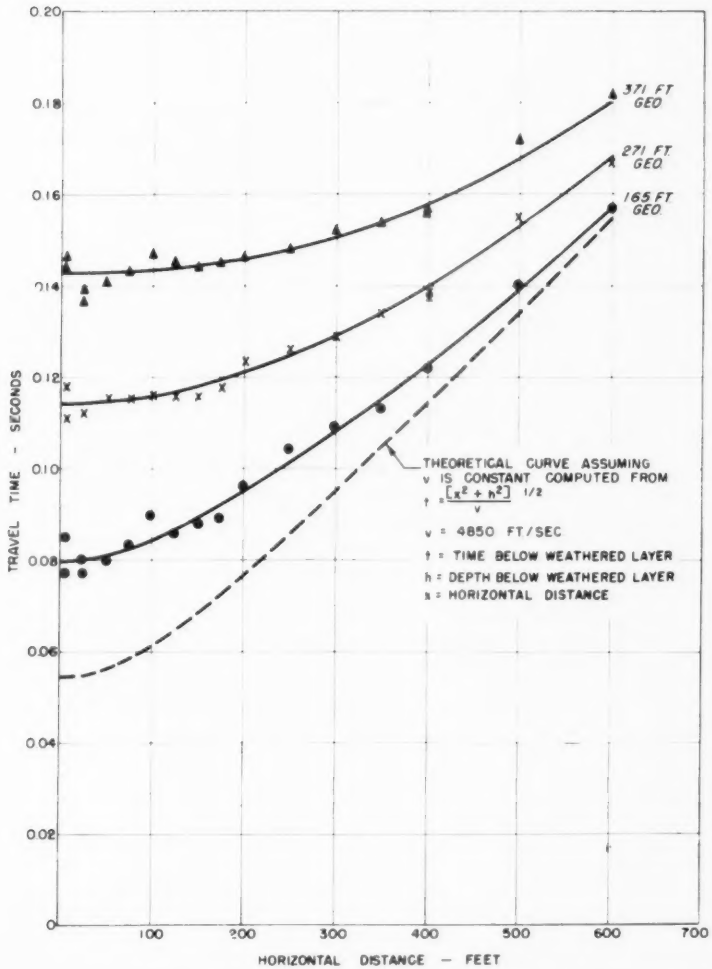

FIG. 11. Time-distance curves of direct SH wave observed at depth.

polarities were found to be erratic, and a point could be located where the amplitude approached zero and the polarity reversed. It was concluded that any apparent SH energy recorded in this region is the result of incorrect geophone orientation and geophone sensitivity to motion broadside to the direction of its movement. It is therefore believed that the tangent circles of Figure 12 give the true directivity pattern, and the dashed line represents experimental error.

SV Wave

An SV refraction profile extending to 275 feet was shot at the same time as the SH refraction profile. The source was turned so that the recoil force was applied *in-line* with the profile, and vertical geophones were used to detect the SV waves. The time-distance data so obtained are shown in Figure 13 together with a typical

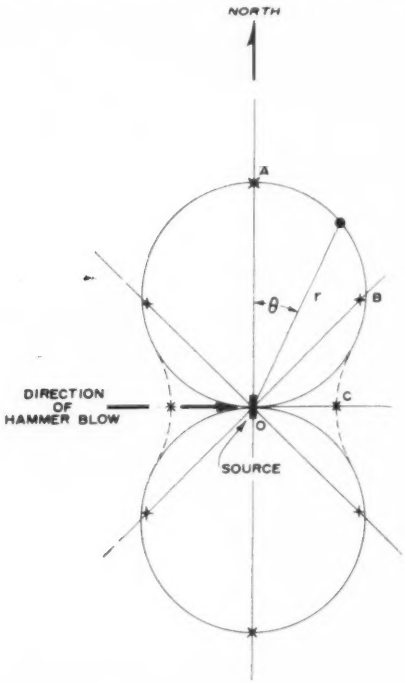

FIG. 12. Directivity pattern for refracted SH waves.

record. The SV refraction is clearly defined, and as before, does not appear on the broadside horizontal traces.

The time-distance plot of Figure 13 has slopes corresponding to velocities of 2,560 ft/sec and 3,180 ft/sec, so that an average SV velocity of about 2,870 ft/sec is indicated. The distances involved range from 60 to 275 feet, and since the weathered layer is relatively thin, it is highly probable that this figure represents the SV velocity in the lower layer. This velocity is strikingly low in comparison with a corresponding SH velocity of 4,850 ft/sec. The data were not sufficient to permit computation of the depth of the weathered layer.

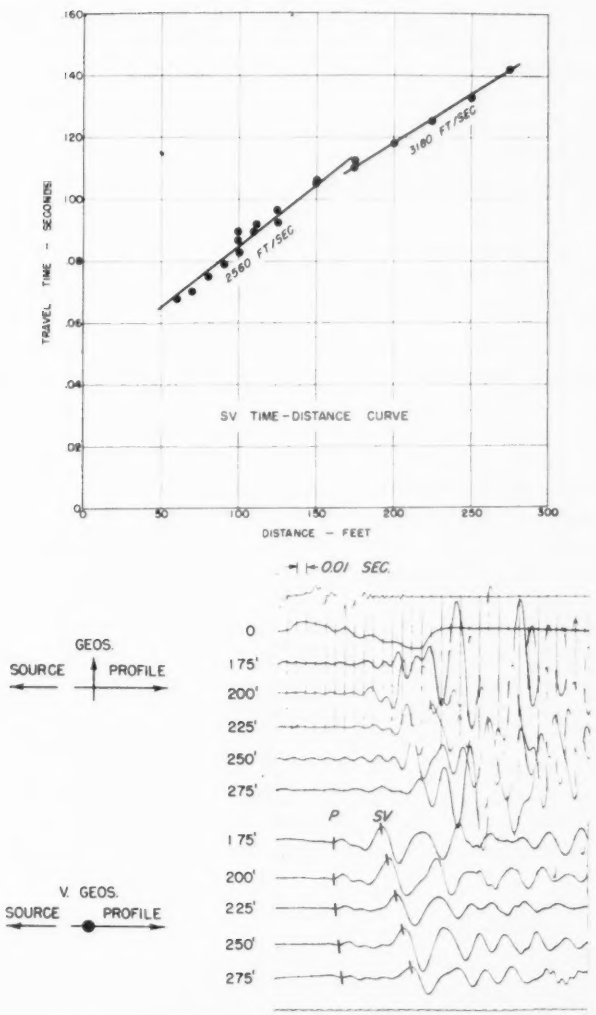

FIG. 13. SV refraction time-distance curve and typical record.

The direct SV wave was investigated in a manner analogous to that used for the SH wave, using both the recoil device and hole shots. Time picks were made of SV events on the vertical traces of records such as those previously shown in Figures 7 and 9, and the SV results, as well as those for SH and P waves, are

plotted in Figure 14. For purposes of comparison, a constant time factor of .019 second was added to the hole-shot SV data. Part of this time difference is due to the fact that there is less low-velocity time for the hole shot, and part may be attributed to the difference in frequency of the two events. It is evident that the time-distance relationship is approximately the same for SV waves from gun and hole shots. Simple theory did not permit calculation of SV curves that would even approximate the experimental results.

P Wave

A reversed profile 375 feet long was shot in the ordinary manner, using shallow hole shots. An upper weathered layer 2 feet thick with velocity 590 ft/sec and an intermediate layer 17 feet thick with velocity 2,675 ft/sec were computed. The velocity determined for the underlying section was 9,500 ft/sec. There was no evidence of dip in the lower interface. The total thickness of the weathered layer, as determined in this manner, is 19 feet, with an average velocity of 1,950 ft/sec. This profile was later extended in one direction to a distance of 1,000 feet. The velocity in the underlying section was still 9,500 ft/sec, indicating that the 400 feet of section under investigation is reasonably uniform.

The experimental time-distance curves of Figure 14 plotted for the direct P wave conform reasonably well with the hyperbolic curves predicted by simple theory. These data are from shallow-hole shots. A vertical velocity survey using P waves was made in an attempt to explain the apparently anomalous SH and SV time-distance curves. In particular, it was desired to determine if appreciable layering and vertical velocity gradient were present. In addition, the tube-wave velocity was to be measured. Data were obtained using closely spaced pressure-sensitive detectors and shallow shots a few feet from the instrument hole. There was no evidence of a vertical velocity gradient or of distinct layering. The measured vertical velocity of 8,500 ft/sec, when compared with the refraction horizontal velocity of 9,500 ft/sec, gives a P-wave anisotropy figure of 12 percent, if anisotropy is expressed quantitatively as the percentage by which the horizontal velocity exceeds the vertical. The tube-wave velocity was found to be 3,970 ft/sec.

Consistency of the Data

A certain amount of consistency in the results of measurements made on the various wave types is to be expected if simple isotropic theory is applicable. Specifically, SH and SV velocities should be approximately equal and should not depend on the direction of wave travel, and the P-wave velocity should likewise be fairly independent of direction. Furthermore, the depth of weathering calculated from P and SH refraction data should be approximately the same (assuming that the P-wave refraction is not from the top of the water table).

The depth of weathering calculated from SH data is twice that obtained from P data. The driller's log showed a very definite lithologic change near the depth given by P-wave refraction and no change at the depth calculated from SH data.

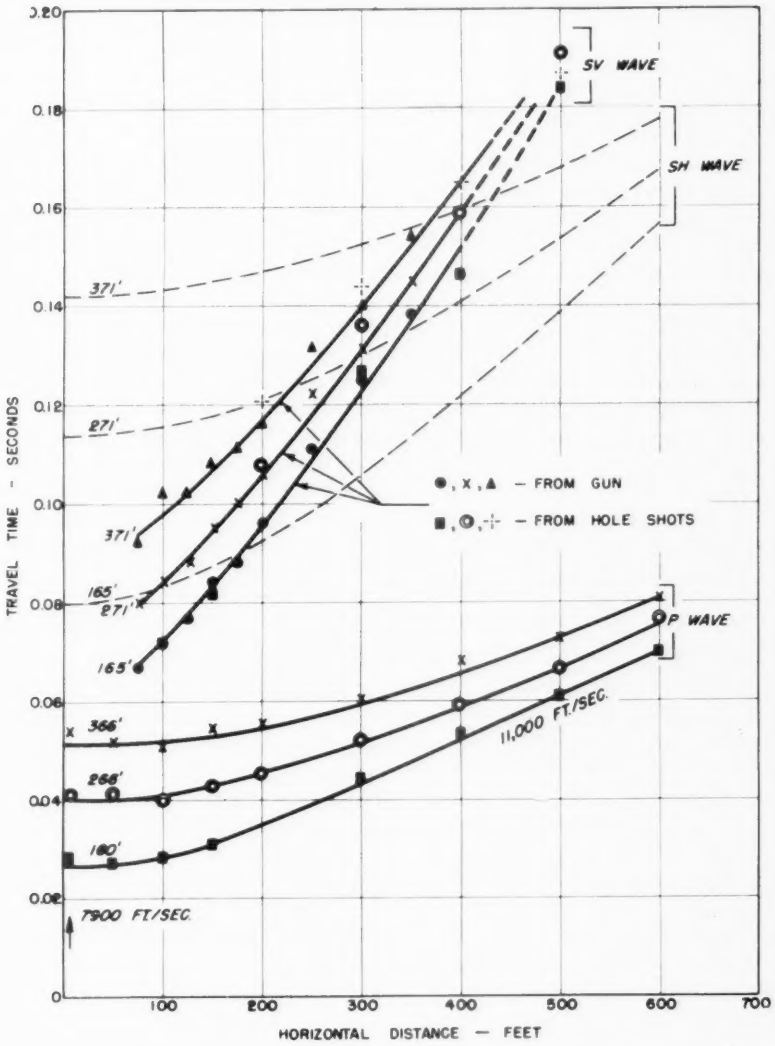

FIG. 14. Time-distance curves of SH, SV, and P direct waves observed at depth.

It is to be concluded therefore that the P-wave figure is correct and that the SH depth should be regarded with a great deal of suspicion.

The SH velocity dependence on angle is strong, and for horizontal travel, SH exceeds SV velocity by a factor of two. Shear wave velocities for vertical travel

are equal, and the horizontal SV velocity approximates the average vertical SH velocity. It is not surprising that the depth of weathering calculated from SH data using the refraction velocity is very much in error. P-wave velocity, on the other hand, is relatively constant with angle of travel and the error introduced by anisotropy is fairly small.

The degree to which the assumption of isotropy is violated can be appreciated by comparison of the SH and SV time-distance curve of Figure 14. They are entirely dissimilar in that their slopes, vertical spacing, and zero intercepts are quite different. It would be expected, since vertical SH and SV velocities are equal, that the curves should coincide at zero horizontal distance. A rather strange-appearing SV curve in the 75-foot transition zone would be required for such to happen. Another peculiarity of the SV wave is the close vertical spacing of the time-distance curves. In fact, if they are extrapolated to zero horizontal distance, the indicated vertical SV velocity is about the same as the vertical P velocity. The P-wave time-distance curves, in contrast to those of SH and SV waves, can be made to approximate those predicted by isotropic theory.

It is evident that the section of earth under observation is far from isotropic, as far as shear waves are concerned. At first sight it would appear that SH and P waves should experience the same degree of anisotropy, but such is not the case. The need for a more realistic theory to account for the various discrepancies and anomalous features of the data is clear.

COMPARISON OF EXPERIMENTAL RESULTS WITH ANISOTROPIC THEORY

Elements of Applicable Theory

A great many articles dealing with wave propagation in an anisotropic medium are to be found in the literature. Several papers published within the past few years are especially pertinent to the type of anisotropy revealed by this series of experiments. White and Angona (1955) and Postma (1955) have shown that a stratified section composed of alternating layers of different elastic materials may be considered as a single homogeneous *transversely isotropic* layer, provided the wave lengths being propagated are large in comparison with the individual layer thicknesses. A transversely isotropic medium is one in which the elastic properties are symmetrical with respect to one fixed direction.

Stonely (1948) was one of the first to investigate plane waves in such a medium and Musgrave (1954) later supplemented Stonely's work by developing the theory of waves emanating from a point source. Postma, in addition to establishing the concept of transverse isotropy in laminated media, covered these theories in a somewhat different manner. These authors show that the outstanding feature of wave propagation in a transversely isotropic medium is the velocity dependence on direction of wave travel.

The measurements from this particular series of experiments were made at distances sufficiently close to the source that plane wave theory is not adequate for comparison purposes. Since the dimensions of the source were small in com-

parison with the wave length of any of the wave types observed, the theory of waves emanating from a point source is considered applicable. The concept of *wave surface*, which Musgrave (pp. 343–345) has indicated to be the envelope of all possible plane wave fronts at unit time, is useful when dealing with such a source, in that the radius vector of the wave surface at a particular angle represents the velocity with which first-arriving energy is propagated outward from the point source. This velocity, presumably, corresponds to that determined experimentally by measuring the arrival time of the first event of the direct wave.

The SH wave surface may be easily determined by finding the envelope of plane wave fronts, using Stonely's velocity equation. This equation, which is valid for any vertical plane containing the source, may be written

$$\rho v^2 = N \sin^2 \theta + L \cos^2 \theta, \tag{1}$$

where ρ is the density, v is the plane wave velocity in a direction making an angle θ with the direction of symmetry (vertical), and N and L are two of the five elastic constants required to specify completely the properties of a transversely isotropic medium. An inspection of the equations of motion from which equation (1) was derived by Stonely reveals that the SH wave is purely transverse for *all* directions of travel.

The wave surface trace in a vertical plane turns out to be the ellipse

$$U^2 = \frac{v_v^2 v_h^2}{v_v^2 \sin^2 \phi + v_h^2 \cos^2 \phi}, \tag{2}$$

where U is the velocity of the direct SH wave (from a point source) making an angle ϕ with the vertical, and $v_v = (L/\rho)^{1/2}$ and $v_h = (N/\rho)^{1/2}$ are the vertical and horizontal SH velocities, respectively. It is more convenient for purposes of comparison to state equation (2) in the time-distance form

$$t = \left[\frac{x^2}{v_h^2} + \frac{h^2}{v_v^2}\right]^{1/2}, \tag{3}$$

where t is the time required for the direct SH wave to travel from the source to a detector located at a horizontal distance x and a vertical distance h from the source. This expression is equivalent to Postma's equation (12) for unit time.

The SV and P wave surfaces are not so easy to formulate. Stonely (p. 345) has also derived the plane wave velocity equations for waves similar to the SV and P types of isotropic theory, which may be stated in the form

$$2\rho v^2 = A \sin^2 \theta + C \cos^2 \theta + L \pm \left\{\left[(A - L) \sin^2 \theta - (C - L) \cos^2 \theta\right]^2 + (F + L)^2 \sin^2 2\theta\right\}^{1/2}, \tag{4}$$

where the *quasi*-P velocity corresponds to the plus sign before the radical and the *quasi*-SV velocity is given by the minus sign. The quantities A, C, F, and L are elastic constants, and the other symbols are as previously defined. A study

of this equation and the determinantal equation from which it was derived reveals that these two wave types are purely transverse or purely longitudinal for horizontal or vertical directions of travel. For other directions their displacement vectors in general deviate from those of true SV or P waves by an amount that increases with the degree of anisotropy. These wave types will henceforth be called SV or P with this reservation in mind.

The envelopes of the wave fronts specified by equation (4) are not susceptible to analytic formulation, and recourse must be had to numerical and graphical methods to determine the shapes of the wave surfaces. Musgrave and Postma have determined P and SV wave surfaces for various values of the elastic constants, and their results indicate that the P-wave surface is smooth and oval-shaped and that the SV surface has several branches separated by singularities or cuspidal edges. The practical significance of these singularities in the SV wave surface may lie in the fact that, for near-vertical or near-horizontal travel and a large degree of anisotropy, the SV velocity can become abnormally large.

Various other geometrical properties of body-type waves in a transversely isotropic medium can be developed from the basic equations derived by Stonely and others. It is sufficient for this comparison to consider briefly the plane SH refracted wave. It may be shown that the ordinary form of Snell's Law is valid provided the velocities are expressed as functions of the angles the ray paths make with the vertical. In particular, if strictly vertical and horizontal ray paths are assumed for a refraction problem, the depth of the weathered layer may be computed from the intercept time and the *vertical* SH velocity.

Surface waves that have an exclusively SH type of particle motion can be propagated in a transversely isotropic medium, provided there is layering present at the surface and if the velocities in the underlying section are greater than those of the surface layer. Such waves have long been recognized by earthquake seismologists and are called Love waves. These waves are generated as a result of constructive interference of SH waves multiply reflected within the surface layer. The interference is such that the original transient separates into sinusoidal components whose phase and group velocities are dependent on frequency.

The dependence of phase velocity on frequency in a transversely isotropic medium may be formulated in a manner analogous to that used by Macelwane and Sohon (1936; pp. 127–132) and others for the isotropic case. The resulting expression in a dimensionless, implicit form suitable for computation is

$$X = \frac{Y(Y^2 - 1)^{1/2}}{2\pi(Y^2 - 1)} \left\{ \arctan \left[E \left(\frac{D^2 - Y^2}{Y^2 - 1} \right)^{1/2} \right] + m\pi \right\}, \tag{5}$$

where $m = 0, 1, 2$, etc. The dependent variable Y is the ratio of the phase velocity of the Love wave to the horizontal SH velocity in the upper medium, and the independent variable X is the product of frequency and vertical SH travel time in the upper medium. The parameters D and E represent physical properties of the two layers, D being the ratio of the horizontal SH velocities and E the product

of the density ratio and the vertical SH velocity ratio. Each ratio is of the quantity in the lower medium to that in the upper.

Group velocity u is related to phase velocity c and wave number k by the well-known formula $u=d(kc)/dk$. This formula may be stated in dimensionless form as

$$Z = \frac{V}{1 - \frac{X}{V}\cdot\frac{dV}{dX}}$$

where Z is the ratio of group velocity to horizontal SH velocity in the upper layer. After performance of the indicated differentiation in equation (5) and some tedious algebra, the following expression for group velocity in terms of phase velocity results:

$$Z = 1/V + \frac{E(D^2 - 1)(V^2 - 1)}{2\pi X(D^2 - V^2)^{1/2}\left[V^2 - 1 + E^2(D^2 - V^2)\right] + EV(D^2 - 1)}. \quad (7)$$

One other type of wave is of interest in this investigation. This is the tube or bore-hole wave, which has been investigated in some detail by White and Sengbush (1953). Their results indicate that such a wave propagates in a transversely isotropic medium with a velocity dependent on the *horizontal* SH velocity. If the tube wave velocity is measured, it is possible to calculate the horizontal SH velocity.

Theoretical Predictions

The following enumeration of theoretical predictions may be made in summary:

1. The SH wave surface is ellipsoidal and a fit of experimental data to curves given by equation (3) will result in values for the constants v_v and v_h.

2. Weathering depth may be computed from SH refraction profiles using an independently determined SH vertical velocity and the intercept of the time-distance curve.

3. *Vertical* SH velocity is identical to *horizontal* SV velocity. This equality is evident from a comparison of equations (1) and (4).

4. The shape of the SV wave surface is complex and the derived time-distance relations will have certain anomalous features. In particular, for near-vertical or near-horizontal travel paths in a highly anisotropic medium, the SV velocity can be abnormally high.

5. Horizontal and vertical SV velocities are equal, as shown by equation (4). SV anisotropy is not expressed by different horizontal and vertical velocities but by departure of the SV wave surface from a sphere at intermediate angles.

6. The P-wave surface is smooth and oval-shaped and can be approximated by an ellipsoid if the anisotropy is moderate.

7. The degree of P and SH anisotropy is not necessarily the same. Inspection of equation (4) indicates that P horizontal and vertical velocities are controlled

by the constants A and C, whereas equation (1) shows SH horizontal and vertical velocities to be controlled by the constants N and L.

8. A dispersive Love wave can propagate in a transversely isotropic medium. Fitting of experimental data to theoretical dispersion curves will result in values of horizontal SH velocity but will not yield unique vertical SH velocities or the layer thickness.

9. The tube wave velocity in this kind of medium can be used to calculate the horizontal SH velocity.

Experimental Confirmation

It is already obvious that the theory of wave propagation in a transversely isotropic medium explains many of the heretofore inconsistent features of the data. Analysis of the experimental results from the standpoint of transverse isotropy, rather than from that of approximate isotropy, appears mandatory.

Time-distance curves computed from equation (3) are fitted in Figure 15 to data points obtained from subsurface measurements of the direct SH wave. These points are the same as those of Figure 11, which could not be made to fit curves computed assuming isotropy. Values of vertical SH velocity were obtained by averaging the time values for the first 50 feet of horizontal distance and assuming vertical ray paths. A trial-and-error process was used to determine the values of horizontal velocity which would best fit the data points at large horizontal distances. It is evident that experimental results agree well with the theoretical curves and that the horizontal SH velocity is about twice the vertical. Furthermore, it appears that although both horizontal and vertical SH velocities gradually increase with depth, the degree of anisotropy remains constant. If the horizontal SH velocity of 5,000 ft/sec obtained from the 165-foot subsurface geophone is compared with the 4,850 ft/sec obtained from SH refraction shooting, it is seen that the data from different types of measurements are consistent. It is quite clear that the theoretical prediction of an ellipsoidal SH wave surface is amply confirmed by the data and that the time-distance curves of the direct SH wave need no longer be considered anomalous. The satisfactory fit of data to curves computed assuming *homogeneous* transverse isotropy indicates that the direct SH wave travels along reasonably straight paths, in spite of the fact that a vertical SH velocity gradient is indicated.

Transversely isotropic theory offers a more realistic means of obtaining the depth of weathering; namely, the use of the *vertical* SH velocity in the weathered layer and the intercept of the refraction time-distance curve. Actually, it was not possible to measure this vertical velocity directly, and it was therefore necessary to make the assumption that the vertical velocity in the weathered layer, like the vertical velocity in the underlying layer, is about half the horizontal velocity. Such a computation yields a weathered layer thickness of 19 feet, in exact agreement with results from the P-wave refraction profile. Conversely, if the reasonable assumption is made that the weathered layer depth calculated from P and from SH refraction profiles should be the same, then it follows that

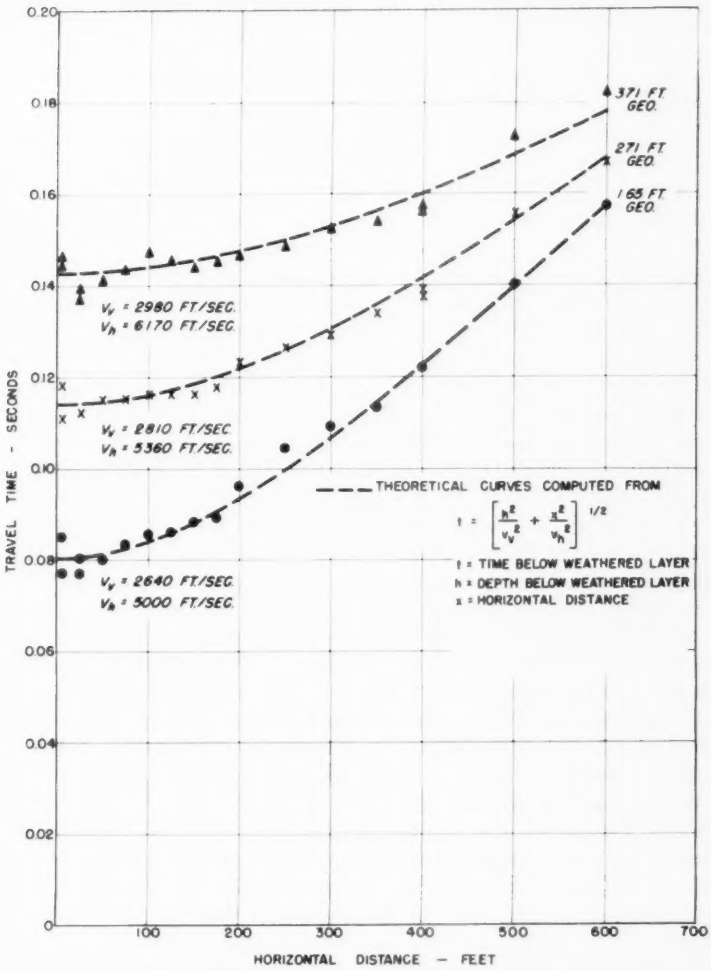

FIG. 15. Comparison of SH direct wave data with theoretical time-distance curves computed, assuming transverse isotropy.

an anisotropy of about 100 percent exists in the weathered layer of stratified sandrock and clay, as well as in the underlying stratified shale section. This removal of the ambiguity in depth of weathering further supports the concept of transverse isotropy.

A comparison of the horizontal SV velocity obtained by refraction shooting and the average vertical SH velocity to the shallowest subsurface geophone

(Figures 13 and 15) supports the prediction that the horizontal SV velocity equals the vertical SH velocity.

Because of the difficulty of determining the constant F in equation (4), it was not considered feasible to compute the wave surfaces for P and SV waves. It is possible, however, to compare the *qualitative* aspects of the P and SV data with some of the qualitative predictions of theory. Theoretical curves may be drawn through the P-wave time-distance data of Figure 14 without serious misfits if a spherical wave surface (no anisotropy) is assumed. Better fits might be obtained if oval or near-ellipsoidal wave surfaces were assumed, but the scatter in the data does not warrant this procedure. It is readily apparent that experimental error and the error introduced by the neglect of anisotropy are of the same magnitude. It has already been pointed out that such is not the case for SH waves, and the same holds true to an even greater degree for SV waves.

The slopes of the experimental SV curves of Figure 14 are roughly equivalent to the *equal* horizontal and vertical SV velocities previously determined, but the spacing between curves, at least for near-vertical ray paths, is about the same as that for P waves, indicating an apparent near-vertical SV velocity equal to the P wave velocity. Such behavior is theoretically conceivable if the SV wave surface has a severe, near-vertical cusp. The existence of SV wave branches is supported qualitatively by the fact that two fundamentally different SV waves have been observed. It is easy to visualize that the vertically-traveling SV wave, identical to the SH wave, becomes less prominent as horizontal distance increases and that the branch represented by the curves of Figure 14 takes over at rather small horizontal distances. Such an explanation would remove the necessity for connecting the SV and SH curves of Figure 14 at zero horizontal distance. Although it is apparent that additional experimental and theoretical work would be required to substantiate fully the existence of SV wave branches, the experimental SV data seem to confirm amply the prediction that the SV wave surface is complex and that higher than "normal" SV velocities are possible. A further complication in the SV wave surface, beyond the scope of the present theory, is introduced by the presence of a vertical velocity gradient which apparently affects the SV wave much more strongly than the SH. It is believed, however, that the effect of curved ray paths is of negligible importance in the present discussion, in that attention has been restricted to near-vertical travel paths.

The theoretical prediction that P and SH anisotropy depend on different elastic constants and are in general different is confirmed by the observed anisotropy figures of 12 and 100 percent for P and SH waves, respectively. P-wave anisotropy values ranging from 10 to 40 percent, as determined in a number of previous investigations, are listed by Uhrig and Van Melle (1955); SH values, on the other hand, are almost completely missing from the literature. White and Angona quote figures for experimentally determined horizontal SV velocity and derived horizontal SH velocity which result in an SH anisotropy figure of 60 percent for Eagle Ford shale and 3 percent for Austin chalk. The corresponding

values for the P wave are 33 and 18 percent, respectively. Measurements made by these authors in a loose sand section indicated almost no anisotropy to either P or SH waves. The main implication in all the data available is that SH anisotropy is very sensitive to the degree of stratification and may be quite large, whereas P anisotropy is less dependent on stratification and is usually relatively small.

The predictions of theory with regard to Love waves can be conveniently evaluated by comparing theoretical dispersion curves, computed from equations (5) and (7), with experimental dispersion data derived by the method of Pekeris (1948) from records such as those shown in Figure 6. Such a comparison is given in Figure 16, where theoretical curves have been chosen to give the best fit to the data points. The horizontal SH velocities used to compute these curves correspond fairly closely to those independently determined by refraction shooting. It is not surprising, in view of the neglect of higher modes and of the other simplifying assumptions made in the theoretical development, that the quantitative agreement of the experimental data with theory is only fair or perhaps even poor. However, from a qualitative viewpoint, it seems safe to state that the surface wave observed has a close resemblance to the theoretical Love wave, if for no other reason than that it is dispersive and its particle motion is exclusively SH.

Computation of horizontal SH velocity from the observed tube wave velocity using the formula of White and Sengbush yields a figure of 5,130 ft/sec, which agrees reasonably well with the refraction figure of 4,850 ft/sec and the subsurface value of 5,000 ft/sec.

It appears that most of the experimental data point to the fact that the section of earth under observation *must* be considered transversely isotropic. Conversely, if the concept of transverse isotropy is accepted, then all data heretofore considered anomalous fit into a perfectly logical pattern. It is to be noted, however, that the theory considered really covers a very narrow, geometrical range, and that a general treatment would require the solution of a boundary value problem of formidable proportions. Such a development would be required to evaluate directivity and other wave properties pertaining to amplitude.

SH REFLECTION RECORDING

Reflection results were entirely negative in three of the four areas tested. The failure to record SH reflections must be attributed primarily to the presence of strong Love waves which blanket possible reflections. Attempts to attenuate this type of interference to a sufficiently low level by the use of multiple geophones, filtering, and mixing were unsuccessful due to the overlapping frequency and wave length spectra of Love wave and reflected energy.

The reflection profile of Figure 17, recorded unfiltered and with fixed gain, is typical of the results obtained in most areas. All coherent events, such as A, are of the Love wave type, and there are no indications of energy having a reflection step-out. The situation could not be materially improved by the use of filtering,

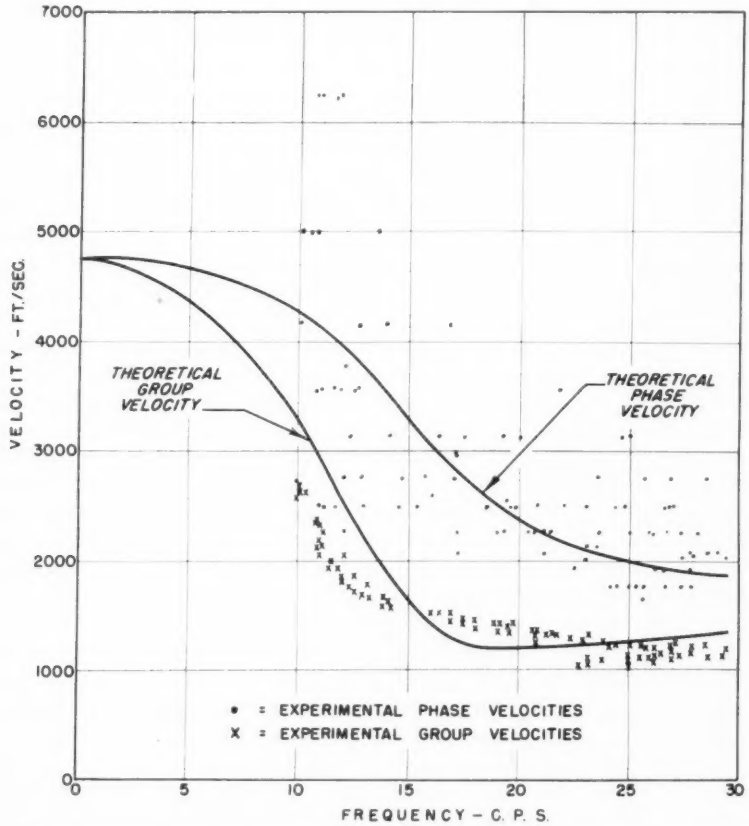

FIG. 16. Comparison of Love-wave group and phase velocities with theoretical dispersion curves that best fit the data. The curves shown were computed using the values $D=3$, $E=2$, horizontal SH velocity and vertical travel time of 1,580 ft/sec and .014 second, respectively.

mixing, AVC, or different spread distances. Records such as these were obtained in areas where the weathered layer thickness ranges from 5 to 200 feet and the underlying section is hard limestone, sandstone, or shale. Shallow reflectors well within the range of the source strength used were known to be present.

SH reflections were successfully recorded at a location near Sand Springs, Oklahoma, where there is a 76-foot layer of loose sand overlying a thick sandstone section. The compressional wave velocities are about 1,800 and 9,000 ft /sec for the sand and sandstone, respectively. A trace coverage of 30 feet and a trace separation of 10 feet were used. Source-detector distances ranged from 25 to 225 feet.

Flat response, fixed-gain records for the shorter spread distances are shown in Figure 18. The top record was taken at low gain and the bottom record at high gain, under identical conditions. Event A on the top record is the Love wave arriving ahead of the reflection (event B). On the bottom record, events C and D appear to be the first and second multiples of reflection B. The primary reflection could not be followed to a distance much greater than 75 feet because of the interfering Love wave. Time-squared versus distance-squared plots made

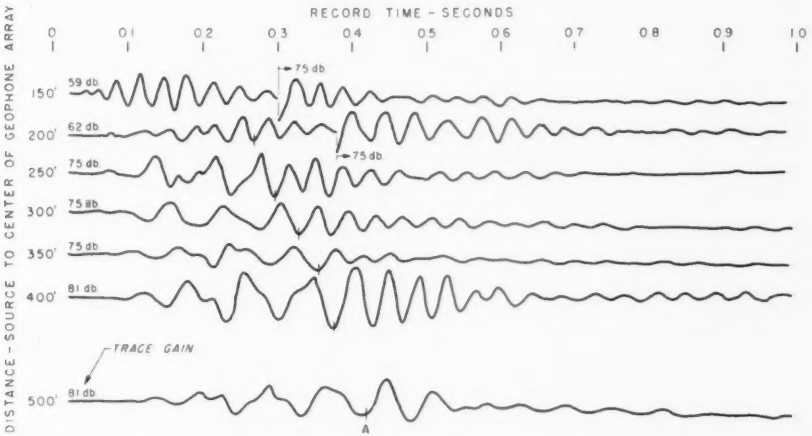

FIG. 17. Typical SH reflection profile using multiple geophones and transverse shear source.

for these events scatter about straight lines, indicating that B, C, and D are reflections. The average SH velocity and depth calculated were 865 ft/sec and 75 feet, in good agreement with the known compressional velocity and thickness of the sand section. It is noted that the Love wave, presumably generated in the uppermost weathered layer, terminates barely ahead of the reflection, and it is perhaps fortuitous that the primary reflection is not obscured by this interference.

An SV reflection profile was shot in this same location by orienting the source and detectors in line with the profile. Although a reflection from the base of the sand section was recorded, it was considerably poorer in quality than that obtained by SH shooting.

CONCLUSIONS

The results of this investigation indicate that reasonably pure shear waves, either of the SH or SV type, may be generated by the application of an unbalanced horizontal force to the earth's surface. The recoil device, because of its simplicity, maneuverability, and relatively high energy output, proved to be quite satisfactory for both fundamental studies and the evaluation of SH reflec-

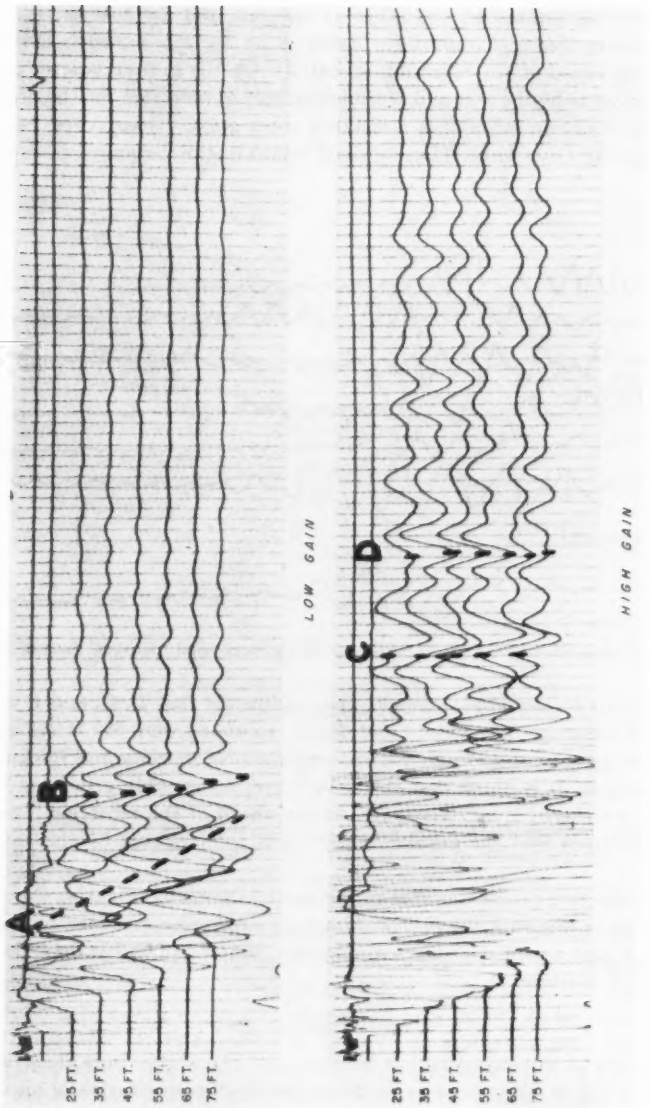

FIG. 18. SH reflections from base of thick weathered layer.

tion recording. This particular source was especially useful in the fact-finding phase of the investigation, in that it generated source-polarized shear waves and thereby provided an extremely useful means of wave-type identification. The similarity of time-distance curves obtained from gun and hole shots provided a basis for identifying the shear-like event from hole shots as a direct SV wave, thus supporting the general belief that appreciable shear energy of the SV type is generated by subsurface explosions. There were no indications whatever of SH energy from such a source.

Studies of direct and refracted SH, SV, and P waves demonstrated conclusively that the stratified shale section under consideration is highly anisotropic to shear waves while being only slightly so to P waves. Anisotropy of the SH wave was manifested by the fact that the horizontal velocity was twice the vertical velocity; and that of SV waves was revealed by abnormally high velocities for near-vertical ray paths and by the presence of what are apparently two branches of the SV wave. All unusual features of the data could easily be explained by considering the elastic symmetry to be that of a transversely isotropic solid. Theoretical predictions, such as the equivalence of vertical SH and horizontal SV velocity, the equality of vertical and horizontal SV velocity, the ellipsoidal shape of SH wave surfaces, and the complex nature of SV wave surfaces, were all confirmed experimentally.

A strong, well-developed surface wave with SH-type particle motion proved to be very similar to the theoretical Love wave. Although the quantitative agreement between experiment and theory was somewhat disappointing, the dispersive properties of the disturbance observed sufficiently resemble those of the Love wave to permit its identification as such. Fitting of theoretical dispersion curves to the observed data provided values of horizontal SH velocity that were in agreement with velocities determined independently by refraction shooting and subsurface measurements.

Attempts to record shallow SH reflections were in most instances unsuccessful. This failure may be attributed to the overwhelming masking effect of the ever-present Love wave, which could not be sufficiently attenuated by any reasonable combination of multiple geophones, filtering, and mixing. SH reflections were recorded at one exceptional location where an unusually high Love wave velocity permitted the reflection to arrive after the termination of the interfering disturbance. An abnormally high velocity ratio of about five at the reflecting interface very likely contributed to the success at this location.

The results of this investigation clearly indicate that shear waves have a very limited application in seismic prospecting. Although it is possible to map shallow interfaces by shear refraction shooting, the ambiguity introduced by excessive anisotropy requires both SH and SV profiles for a unique depth determination. Such information may be obtained much more conveniently by the use of compressional waves. Love wave dispersion data, while providing semi-quantitative velocity information, do not yield a unique depth determination. It appears likely

that SH reflections cannot be recorded in the majority of areas with a reasonable expenditure of effort, and that such reflection data, even when obtained, would be difficult to interpret. The further difficulty of obtaining sufficient source strength for exploration to the usual depths is likewise evident. SV waves, because of their extremely curved ray paths, are even less likely to have a practical application in reflection prospecting.

The value of the results derived from this investigation obviously lies in their fundamental, rather than immediately practical, nature. Certain generally unrecognized properties of shear waves have been determined conclusively, by closely controlled experiment, apparently for the first time. In particular, it has been definitely established that the assumption of transverse isotropy in stratified sections of the earth is valid, and that anisotropy of this type must be considered in shear or surface wave studies. It is felt that some aspects of this investigation may be of special interest to earthquake seismologists, who deal routinely with shear waves, as well as to those exploration geophysicists who are engaged in fundamental seismic research.

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GEOPHYSICS, VOL. XXI, NO. 4 (OCTOBER, 1956), PP. 939-959, 9 FIGS.

SEISMIC WAVES FROM A TRANSDUCER AT THE SURFACE OF STRATIFIED GROUND*

F. F. EVISON†

ABSTRACT

Vibration impulses of variable frequency and duration have been generated by means of an electrically excited vibrator and the resulting seismic waves recorded at the ground surface along a 200-ft traverse. The first arrivals were refractions from the water table and a deeper clay-siltstone interface, and these checked with the results of a standard refraction survey. The amplitudes of displacement of the refracted waves varied in each case with approximately the inverse square of distance; the critical distance was marked by a discontinuity of amplitude. Two later impulsive arrivals recorded within 50 msec of the first were interpreted respectively as a transformed reflection from 85 ft depth and an ordinary compressional reflection from 200 ft depth. A dispersive Rayleigh wave gave an independent estimate of the shear velocity and thickness of the surface layer. Air-coupled waves of frequencies 70.8 cps and 330 cps were recorded and have been related to the first- and third-mode Rayleigh waves respectively.

INTRODUCTION

The propagation of artificial seismic waves in shallow rock strata has been studied primarily, as in prospecting, in terms of the travel-time of body waves—direct waves, refracted waves, and, for depths of penetration greater than about 400 ft, reflected waves. Close to the conventional explosive source the motion is complex, especially in stratified ground, and on the other hand propagation beyond quite small distances is usually affected by the natural irregularity of the ground. Substantial advances in the understanding of seismic propagation are more readily achieved in other fields where the media are comparatively uniform. Marine and crustal seismology have lately produced elaborate studies of dispersive waves; the phenomenon of air-coupling was first elucidated as a result of experiments on floating ice-sheets; and quantitative observations of the partition of energy at a rock boundary have been mainly confined to earthquake seismology. At the other extreme there is a growing interest in laboratory studies of propagation by means of very short waves in simplified model media.

The present study involves several types of seismic wave propagated over distances up to a few hundred feet in ground that was tolerably though not exceptionally uniform. By using a transducer as source it was possible to generate impulses having comparatively regular waveforms, and the usual non-elastic motion near the source was avoided; moreover, the waveform could be easily varied to suit the particular phenomenon under observation. This type of source may perhaps facilitate the study of certain seismic wave phenomena by means of small-scale experiments in ordinary ground, particularly phenomena in which frequency and amplitude are involved.

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The source was a moving-coil transducer of the Fessenden type, developed from an oscillator formerly used by the British Admiralty for underwater signalling and depth-sounding. Details of the construction of the transducer have been published previously (Evison, 1951 and 1953), and H. Pursey has recently completed a rigorous analysis of its radiation characteristics (Pursey, 1956). An 84-volt bank of accumulators supplied the current for the electromagnet and also, through a commutator, that for the alternating field. The latter current could be varied in frequency by varying the commutator speed, and its duration could be controlled by means of a relay-switch energised by the discharge of a variable capacitance. In this way the radiated seismic impulse could be given any of a variety of frequencies and durations. For most of the observations described below, a waveform consisting of one or two half-cycles was found satisfactory, with durations varying up to 10 milliseconds.

The earlier experiments were conducted in various underground tunnels where the transducer was bolted to solid rock. Here for the first time the transducer has been applied at the ground surface, and to an incompetent stratum; for this purpose it was mounted on a piston, of diameter 4 feet, which was coupled to the ground by means of a layer of mud.

The geophone, amplifier, and camera were of the standard types used in prospecting. Unwanted frequencies were excluded from the record by the use of variable band-pass filters with sharp cut-offs. A description of these filters and the arrangements for monitoring, triggering, and recording the transducer impulse has also been given elsewhere (Evison, 1953). Each record showed the transducer impulse on the upper trace and timing-lines at intervals of 10 milliseconds. The sensitivity of the receiver was approximately constant for equal displacements over the relevant ranges of frequencies. A well geophone used for vertical velocity determinations was fitted with a clamping device to give positive contact with the walls of the borehole.

Standard prospecting apparatus was used to carry out a shallow refraction survey of the site. Part of this survey was duplicated with the transducer, allowing a comparison of the two methods. The single receiver channel included in the present experimental apparatus does not suit it for extensive surveys, nor are multiple channels so advantageous for recording features other than the onset of first arrivals, since it is usually necessary to adjust the apparatus afresh for each geophone position. Such adjustment is readily performed when the source is a transducer capable of delivering an impulse every few seconds.

SITE

The experiments were carried out on a flat river-terrace at Makara township near Wellington, New Zealand, most of the observations being made along a 200-ft line with the transducer at one end. The transducer was 49 ft from a borehole drilled some years previously for which the driller's record, based on washings,

has been included in Figure 2b. Details of the shallower layers as indicated by the standard refraction survey are shown in Figure 1. Two thin surface layers with velocities 0.80 ft/msec and 5.33 ft/msec, respectively, overlie a medium with velocity 7.19 ft/msec; this substratum velocity was found from refraction measurements beyond the 200-ft line, so that the apparent velocities for the second refractor on the line indicated the change of dip shown in Figure 1. Here, as elsewhere in this study, the observations were analysed by the method of least squares to allow a close comparison of results. The standard errors were omitted from subsequent calculations, but the existence of a slight dip in the first refractor was tested statistically and found to be significant.

An unusual feature may be noticed in Figure 1 in the interpretation of traveltimes around the distance 75 ft. For the shot at 0 ft, and again with the transducer (see Figure 2a), the first arrival at 75 ft came from the first refractor where an

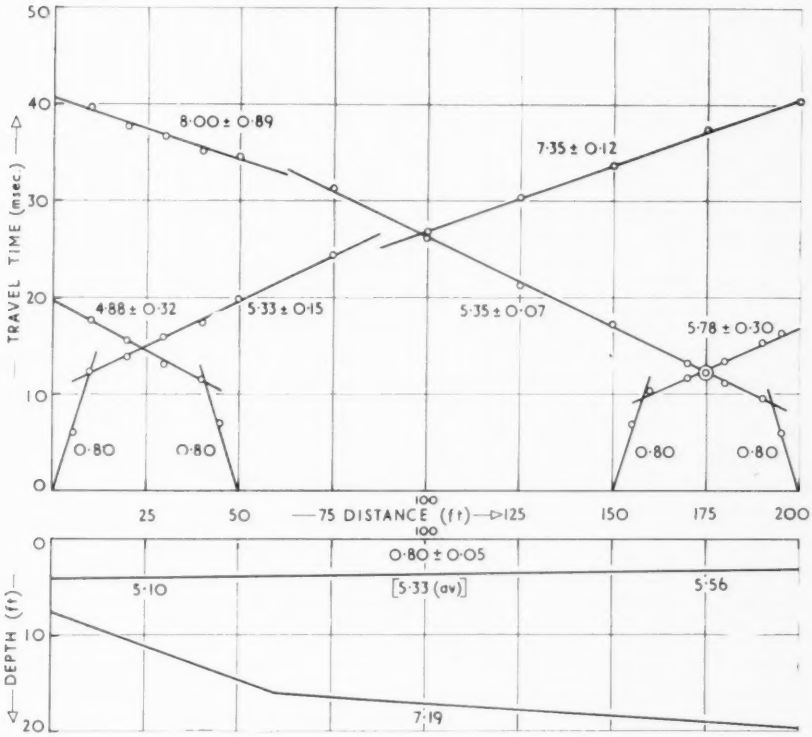

FIG. 1. Results of standard seismic refraction survey. (Velocities are given in ft/msec.)

DATA FOR FIGURE 2

Travel-times (see Figure 2a)

Distance (ft)	10	20	30	40	50	75
T_1 (msec)	9	11½	13	14	17	22

Distance (ft)	100	125	150	175	200
T_1' (msec)	24	28	31½	34	38
T_2 (msec)		48	50½	52½	55½
T_3 (msec)	68	67½	68½		

(All times include correction +1.5 msec for depths of vibrator and geophone.)

Driller's record (see Figure 2b)

A. 0–8 ft: Brown rusty metal, medium size (sub-angular weathered greywacke).
B. 8–220 ft, 232–350 ft: Soft blue silty clay with shells (uncemented siltstone).
C. 220–232 ft: 60 percent clean "pea-metal," 40 percent blue clay with shells.
Below 350 ft: Hard blue greywacke (indurated sand-stone).

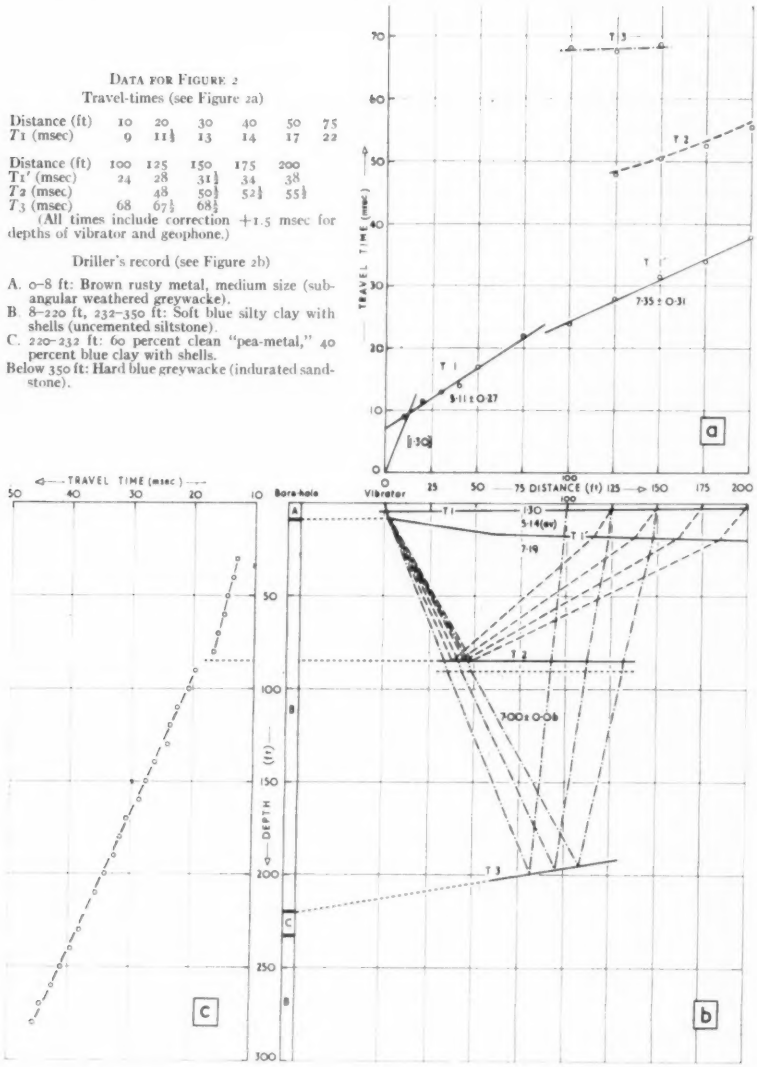

FIG. 2. Results of travel-time observations with vibrator as source. (a) Travel-times along traverse of Figure 1. (b) Interpretation of (a); driller's record. (c) Travel-time in borehole.

earlier arrival would ordinarily have appeared from the second refractor. This peculiarity was due to the change of dip in the second refractor, a feature which was also indicated by measurements of amplitude to be described later.

Seismic travel-times were measured from the transducer to various depths at 10-ft intervals in the well and are plotted in Figure 2c. The times to depths between 90 ft and 280 ft were used to compute the seismic velocity for this interval (7.00 ± 0.06 ft/msec), allowing for slanting ray-paths. The times to shallower levels were unsuitable for such computations, being too much affected by refraction in the surface layers, but a discontinuity was clearly indicated between 80 ft and 90 ft.

The seismic properties of the site could be described as fairly typical of regions where geologically recent sediments overlie bedrock.

BODY WAVES

The vibrations recorded along the 200-ft traverse with the transducer as source varied considerably in character as the form of the radiated impulse was varied, but in general the arrivals occurred in two groups. A succession of impulsive arrivals tending to overlap at shorter distances occupied the earlier part of the records; the later part was dominated by more or less prolonged trains of waves. It has been shown by Newlands (1952) for the comparable case of a line source that energy which travels along the minimum-time paths predicted by ray theory retains the impulsive character of the source. Thus the early arrivals have been interpreted as body waves. The wave trains on the other hand were surface waves, and will be discussed later.

The easiest arrival to interpret was the first, which is of course the only body wave arrival commonly studied in seismic prospecting at shallow levels. Figure 3 shows a series of records obtained with an applied impulse in the approximate form of a single sine wave of duration 5 milliseconds, and a filter pass-band of $92\frac{1}{2}$–860 cps. The gain of the receiver was varied to give comparable deflections at all distances. The onset of motion was not as sudden as is usually experienced with the explosive source, and so arrival-times have been read from peaks. This method of reading is valid so long as the shape of the impulse does not vary with distance; inspection of Figure 3 fails to reveal any progressive broadening of the impulse such as that described by Ricker (1953) for direct waves in shale, nor do the relative amplitudes of the first few half-cycles vary significantly. The distances involved were perhaps too short for frictional losses in the ground to affect the waveform noticeably. An advantage of reckoning travel-times from peaks is that they are not affected by the gain of the receiver in the way that Ricker has shown onset-times to be.

The first half-cycle of the first arrival was small, and in Figure 3 can be clearly seen only at the shorter distances. At the greater distances the travel-time was deduced from the time of the second peak. Two sets of first arrivals are shown in Figure 2a, representing the first and second refractors and labelled T1 and T1′

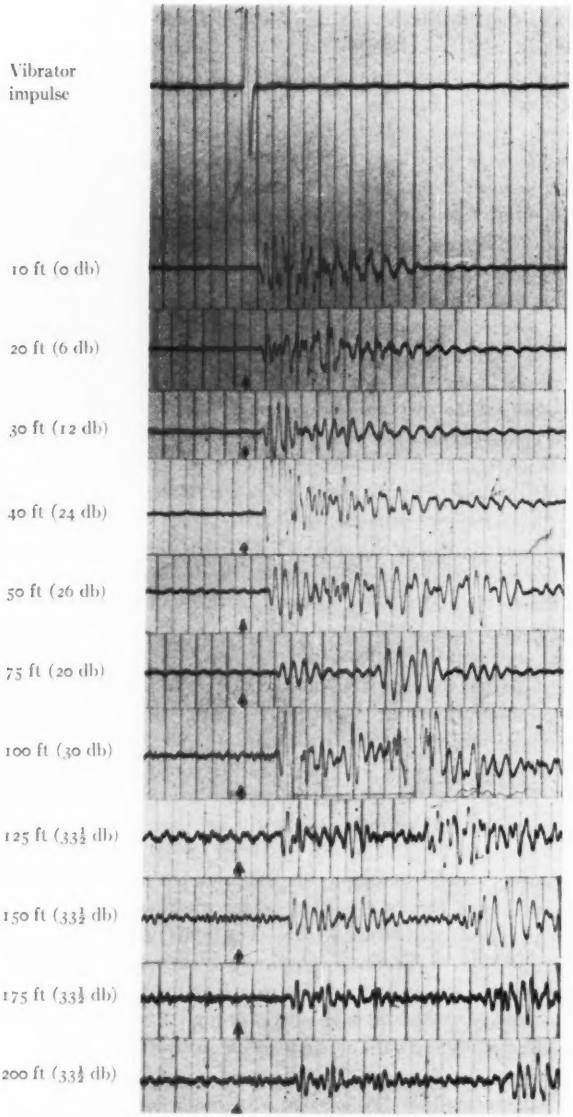

FIG. 3. Vibrations recorded along 200-ft traverse with vibrator as source. The time of the first peak of the vibrator impulse is shown on each record by an arrow, and the relative receiver gain is shown in decibels. Timing lines are recorded at intervals of 10 msec.

respectively. The direct compressional wave through the thin surface layer did not appear as a first arrival, but the refractions may be seen to have arrived consistently earlier than in the standard survey, and an approximate velocity 1.30 ft/msec will be derived below from an analysis of the surface waves. Such a change in the properties of the surface layer between the two surveys, which were separated in time by a period of several months, might possibly be caused by differences in the water content. The first refractor was assigned an average velocity as shown in Figure 2b by assuming the same proportional variation of velocity along the 200-ft line as that found from the standard survey (Figure 1). From this assumption and the data in Figure 2a it follows that the depth of the first refractor at the transducer was 4.6 ft and the dip 0.6 degree upwards along the line. The corresponding values for the standard survey were 4.1 ft and 0.3 degree respectively. The difference in dip cannot be guaranteed, since the transducer was operated from only one position, but the difference in depth is believed to be due to the dissimilar waveforms of the refracted energy in the two cases, and will be referred to below.

Two later impulsive arrivals have been identified. These are shown most clearly in the records of Figure 4, for which the transmitted waveform was adjusted to suit each successive distance; they are also recognisable in the corresponding records of Figure 3. A general resemblance between the first and third arrivals may be noted, while the second arrival appears to be reversed in direction. On this basis the time of a second or third arrival was measured in relation to a corresponding phase of the first arrival, the known travel-time of which was then added. The travel-times thus determined from Figure 4 are plotted in Figure 2a. (It will be shown below that these times probably include a small systematic error.) Both later arrivals gave apparent velocities considerably greater than any given by the refractions. An interpretation has been based on the reconstruction of ray-paths for those arrivals, marked in Figure 4, which could be timed without ambiguity. Several less distinct arrivals lend support to the interpretation.

The second arrival has been interpreted as a "transformed reflection" from a depth of 85 ft, the impulse travelling downwards from the vibrator in the shear mode and returning to the surface in the compressional mode. Figure 2b shows ray-paths constructed on this postulate and Figure 2a the time-distance graph corresponding to them. The requisite shear velocities for the second and third layers were inferred on the assumption that Poisson's ratio was 0.25 for both layers. The time-distance graph lies close to the observed travel-times. As has already been mentioned, measurements with the well geophone indicated a sudden increase of travel-time between 80 ft and 90 ft, and the velocity of the siltstone below 90 ft also appeared somewhat lower than that of the second refractor. The reversal of phase suffered by the second arrival may thus be attributed to reflection from a layer of smaller acoustic impedance. The well log for the seismic shothole suggests a thin layer of soft material, and it is perhaps not surprising that the driller made no mention of such a layer, especially as the rate of drilling in the siltstone was reported to be very fast.

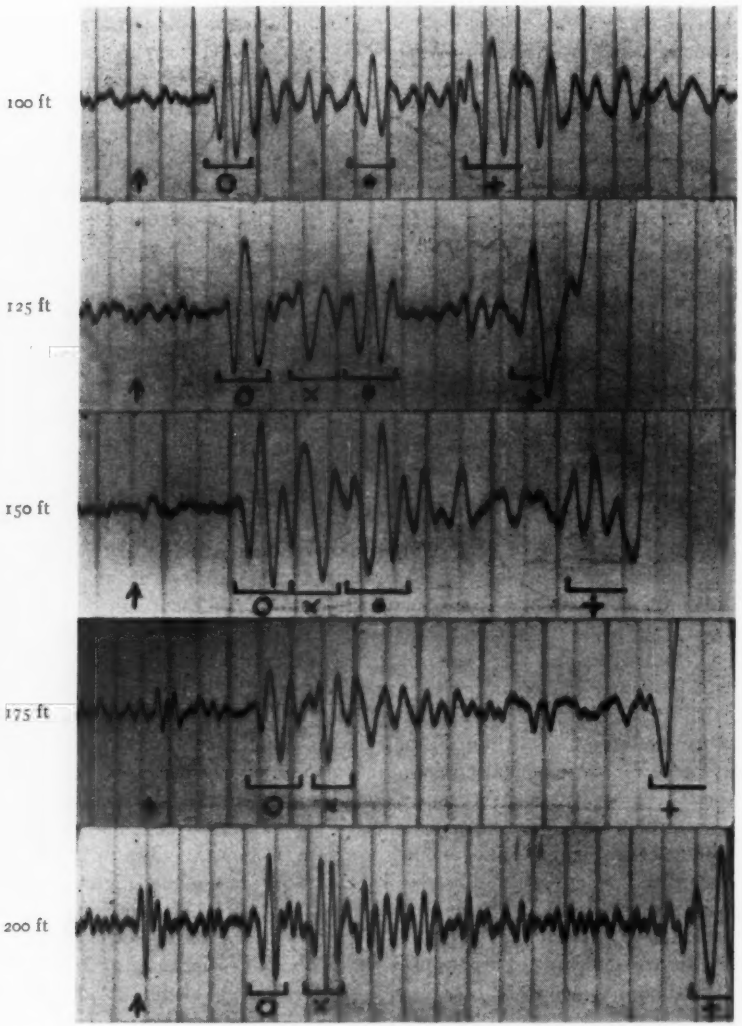

FIG. 4. Early arrivals. ○ arrival $T1'$; × arrival $T2$; ● arrival $T3$. (See Figure 2). + beginning of surface waves.
Duration of vibrator impulse: $2\frac{1}{2}$ msec. for 100 ft, 5 msec for 125–200 ft.
No. cycles in vibrator impulse: $\frac{1}{2}$ for 100–150 ft, $\frac{3}{4}$ for 175 ft, 1 for 200 ft.
Pass-band: $92\frac{1}{2}$–860 c/s for 100 ft and 200 ft; 50–430 c/s for 125–175 ft.
(Arrows indicate times of first peak of vibrator impulse.)

Transformed reflections are uncommon in seismic prospecting, but have been identified by Ricker and Lynn (1950) in several areas in the U.S.A., and Gutenberg (1944) has shown that in earthquake records such reflections may have amplitudes as great as those of direct compressional waves. The transducer generates a large proportion of shear energy, and in this respect resembles the natural earthquake rather than the explosive source; evidence of transformed reflections has been found previously by the author using a similar source (Evison, 1951b). The absence of an identifiable reflection of the ordinary compressional type from the 85 ft boundary has not been adequately explained. It is of some relevance to note, however, that the polar diagrams derived for small pistons by Miller and Pursey (1954) show considerable shear radiation at angles not far from the vertical; and curves compiled by Gutenberg (1944) for small velocity contrasts show that a compressional wave reflected in the medium of greater velocity, at angles similar to those in the present case, carries much the same energy whether the incident wave is compressional or shear.

The third arrival has been interpreted as an ordinary compressional reflection from a dipping interface at about 200 ft. The ray-paths and the corresponding time-distance graph are shown also in Figure 2. Extrapolating the interface to the borehole gives the same depth there as appears in the driller's record for the top of a 12 ft bed of "pea-metal." The time-distance graph is again close to the observed travel times.

Because the interpretation of these later arrivals has been based on a rather small number of observations, travel times have been computed for various other possible paths in and above the second refractor, such as refractions involving transformations of mode. None of these could account for the observations. A further reflection might have been expected from the bedrock, where the velocity contrast was probably about 1.5, though this interface would tend to be screened by the shallower discontinuities. In some records a small arrival has been noticed at an appropriate time for a bedrock reflection (approximately 100 milliseconds), but the same time happens to be appropriate for the direct compressional wave.

Although the body-wave arrivals seem to have a characteristic waveform, closer inspection of Figure 4 suggests that the situation is not quite so simple. There is evidence of the relationship found theoretically by Muskat (1933), that a reflection waveform is the derivative of a refraction waveform from the same source. Allowance for this relationship would strictly invalidate the method adopted above for reckoning the travel-times of the second and third arrivals, but since the error involved is small and for the most part systematic this complication has been disregarded.

This detailed discussion of the second and third arrivals has been given because of the growing interest in the possibility of observing shallow reflections. Recently Pakiser, Mabey, and Warrick (1954) have succeeded in obtaining exceptionally shallow reflections by a modification of the standard reflection technique. The only previous examples noticed in the literature where reflections from depths

less than about 400 ft were observed from the surface of the ground arose in the peculiar case of glacier-sounding.

ATTENUATION OF REFRACTED WAVES

The amplitude of vertical displacement at the surface due to a wave refracted along a shallow interface may be written,

$$a = a_0 r^{-n} e^{-\alpha r},$$

where r is the distance from the source, r^{-n} is the divergence factor, α is the coefficient of absorption in the refracting medium, and a_0 incorporates all factors independent of distance. A more complicated form of divergence factor, due to Cagniard (1939), is required if the depth of the interface is not small compared with the distance from source to receiver, or if the velocity contrast is slight, but the simpler form is adequate for the present purpose.

As Berson (1951) has pointed out, the measurement of n and α may prove useful in seismic prospecting. At great distances from the source the variation of amplitude depends mainly on absorption, and so long as the greatest and least distances at which observations are made do not differ by two large a factor, α may be satisfactorily estimated by assuming a reasonable value of n. Conversely, the variation near the source depends essentially on n, and for ranges limited to a sufficiently small number of wavelengths the effect of absorption is negligible. Thus, in the present case the exponential factor may be omitted, and the amplitude equation may then be conveniently written in the form,

$$A = C - 20n \cdot \log r,$$

where $A (= 20 \log a)$ is the amplitude in decibels and C is an arbitrary constant.

With the present apparatus the deflection recorded with a given setting of the receiver was proportional to the vertical ground displacement. Deflections of the first, second, and third peaks of the first arrival were measured in the records of Figure 3, and corresponding values of A, adjusted for the varying gain of the receiver, are plotted against $\log r$ in Figure 5.

The observations are scattered about two sets of straight lines corresponding to the two refractors. The various values of n were computed by least squares. (It would be difficult to devise a suitable weighting system with the data available, especially where noise is involved, and no weights were applied.) The computed values of n varied from 1.7 ± 0.2 to 2.0 ± 0.5. Substantially the same value was obtained for the various phases of each refraction, confirming that the shape of the impulse did not change with distance. Preference may perhaps be given to the observations of the second half-cycle, which was the least susceptible to distortion by noise on the one hand and by later arrivals on the other. The values of n obtained from this phase ($n = 1.9 \pm 0.2$ for the first refractor and $n = 1.9 \pm 0.3$ for the second refractor) were not significantly different from the theoretical

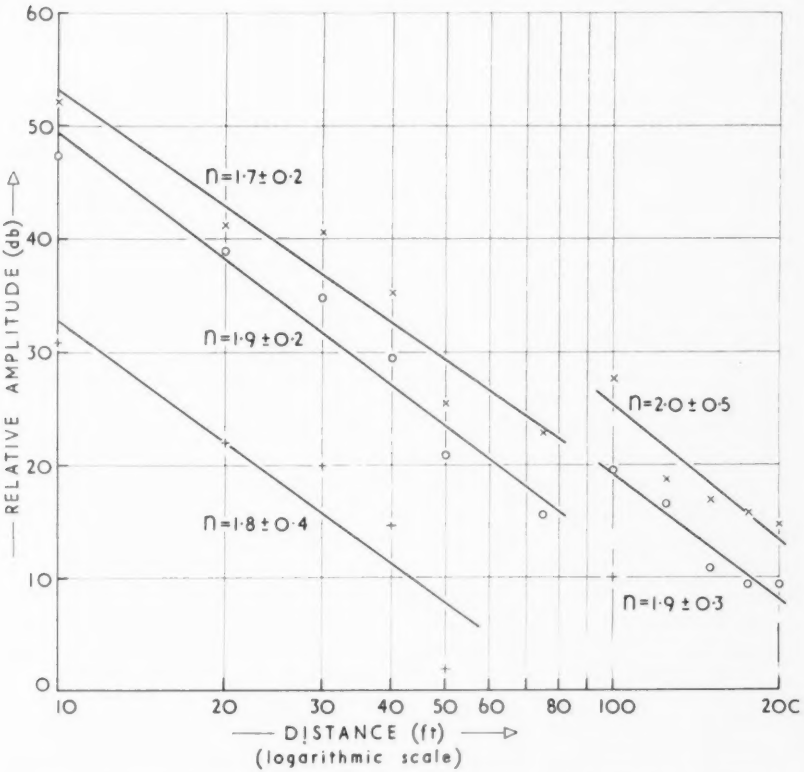

FIG. 5. Attenuation of refracted waves (the first arrivals in Figure 3). + first peak, ○ second peak, × third peak.

value ($n = 2.0$) for refraction along the boundary between two semi-infinite media (Muskat, 1933). The computed values may incorporate a small absorption effect. For example, if $\alpha = 0.16$ per wavelength (i.e. $Q = 20$) for the first refractor the true value of n would be about 1.7; but the absorption is unlikely to have been as large as this.

Few observations of n have been published. From measurements in various types of ground Berson (1951) found a range of values mostly between 1.5 and 2.0. In water-covered areas, Worzel and Ewing (1948) obtained values varying from 1.5 to 2.4, and more recently Officer (1953) has reported the unusually low value 1.25. The theoretical value may differ from 2.0 when the upper medium is bounded. A proportion of the energy refracted into the upper medium is continually reflected at the boundary and returns to make a further contribution to

the energy travelling in the lower medium. If the relative phase of the reflected and refracted waves is constant along the path a continual interference process occurs which affects the value of n for the refracted wave. The process is not effective, however, until some time after the onset of the wave, corresponding to the extra travel-time of the reflected energy. In the present case it can easily be shown that neither refraction could be affected earlier than the third half-cycle. Moreover, the varying thicknesses of the layers would prevent a regular interference process from being established.

The transition from the first to the second refractor in Figure 5 is marked by an increase of amplitude by about 7 db. This difference of level may be attributed in the main to two factors: the proportion of incident energy entering the refracted wave in each case, and, in the case of the second refraction, the partition of energy at the water-table.

Since these factors involve the velocity contrast at the appropriate interface it is clear that in general two waves refracted at different depths will have different amplitudes at any given point of observation, and that when the amplitudes of first arrivals are plotted, a discontinuity will be found at the critical distance. Perkins (1952) has published results showing curves of refracted amplitude intersecting at or near the critical distance, but the case seems coincidental. The discontinuity may prove useful for locating the critical distance in seismic surveying, especially when the observed velocities on either side are not very different. In the present case the amplitude curves were valuable in verifying that the first arrival at 75 ft came from the first and not from the second refractor, and hence that the second refractor was subject to a sudden change of dip as already described.

RAYLEIGH WAVE DISPERSION

The dispersion of a wave-train radiating from an impulsive source is conveniently studied from the variation of travel-time with frequency at some suitable distance. Thus the record from a single geophone suffices to show the relation between group velocity and frequency, and this relation is directly comparable with theoretical dispersion curves. In the case of a single surface layer the shape of the theoretical curve depends on the relative values of the density, and of the elastic moduli, for the layer and the underlying medium. The process of fitting the observations to the appropriate theoretical curve yields values of the shear velocity and thickness of the surface layer.

Dispersion in the surface layer at Makara was clearly displayed by the vibrations produced by a half-cycle impulse at the source. The dispersive wave-train at it appeared at the distance 125 ft may be seen in the first three records of Figure 6, commencing at a travel-time of about 120 milliseconds. An additional low frequency train which interferes with the earlier part of the dispersive train will be discussed later. Figure 6, i and ii, were made in identical conditions and are included to show the extent to which a particular record could be reproduced.

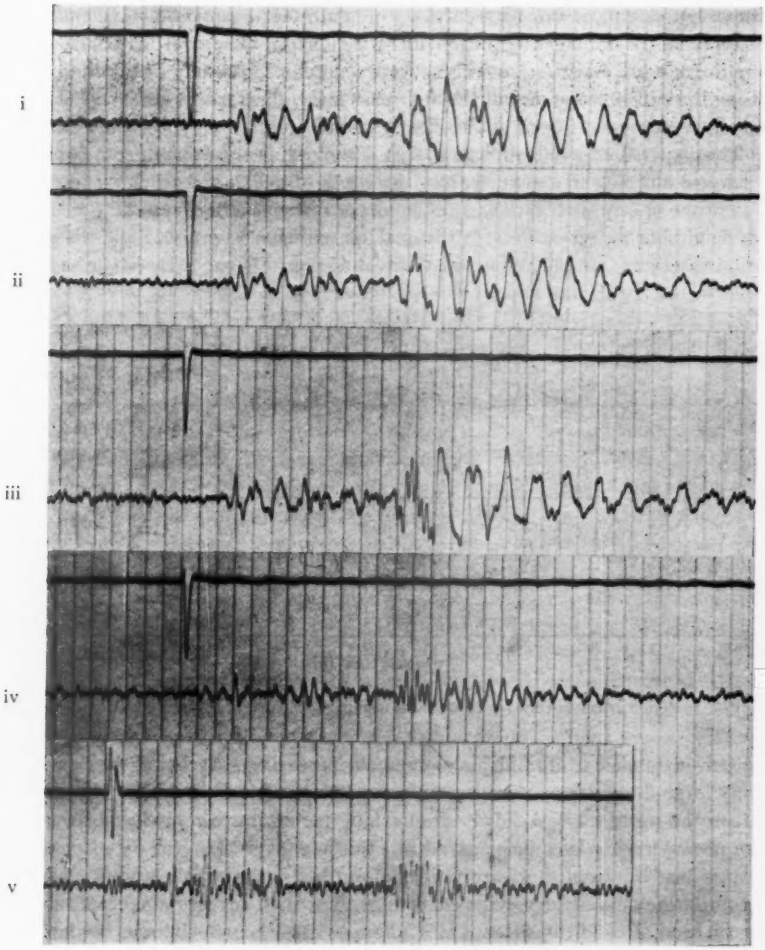

FIG. 6. Records illustrating use of controlled source. (Timing lines are at 10-msec intervals.)

i Transducer impulse chosen to emphasize 1st mode Rayleigh wave-train, commencing at about 120 msec. Distance 125 ft, receiver pass-band 50–430 cps.

ii Repetition of i.

iii Transducer impulse shortened to intensify high frequencies, especially 3rd mode air-coupled wave superimposed on beginning of Rayleigh wave train.

iv Low frequencies excluded by filtering. Receiver pass-band 92½–430 cps.

v Dominant frequency in transducer impulse increased to 330 cps to intensify air-coupled wave. Distance 175 ft, receiver pass-band 92½–1050 cps.

From Figure 6, iii, it can be seen that the main features of the wave-train were not affected by halving the pulse-width; various vibrations of higher frequency were introduced, however, and these were recorded separately in Figure 6, iv, by raising the cut-off frequency of the high-pass filter. The records also show the early body-wave arrivals though not so clearly as in Figure 4.

The dispersive wave train was analysed by reading the times of zero deflection, which are more clearly defined than the times of peaks and troughs; the period at the time of any such zero was taken as the difference between the times of the two neighbouring zeros. Periods thus calculated from Figure 6, i and iii, at half-period intervals, are plotted against travel-time in Figure 7. It will be seen that

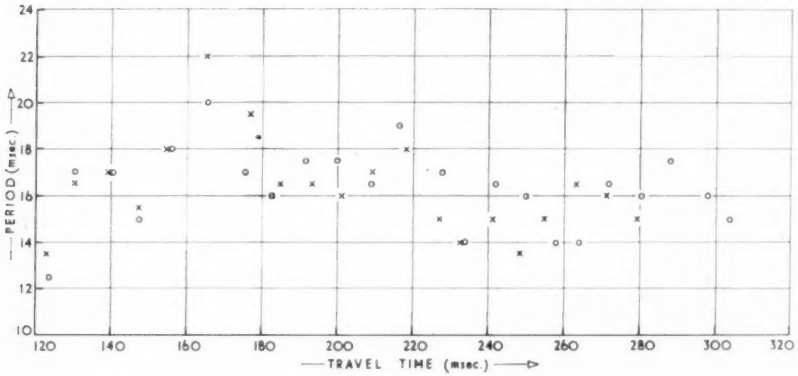

FIG. 7. Period *vs* travel-time for wave trains in Figure 6, i and iii. × Figure 6, i. ○ Figure 6, iii.

the period tended to diminish slowly with increasing travel-time but that relatively large fluctuations were superimposed on this trend, especially in the early part of the wave-train. A slowly diminishing period is a commonly observed feature of Rayleigh waves propagated in a surface layer. The theory of dispersion for this case has been thoroughly worked out but considerable labour is involved in computing curves for specific conditions. Few such curves have been published for the kind of conditions found at Makara, where the velocity was several times greater in the underlying rock than in the surface layer. A satisfactory interpretation has, however, resulted from adopting theoretical curves for the conditions assumed by Lee (1934). Lee computed phase velocities for the case of a layer of clay on granite, taking the density contrast as 1.39, the rigidity contrast as 13.77 and Poisson's ratio as 0.25 for both rocks. The corresponding group velocity curve has been computed by Jardetzky and Press (1952), who pointed out that the assumed conditions were similar to those commonly found at the ground surface. More recently Tolstoy and Usdin (1953) computed three further modes for the same conditions. (The group velocity curve shown by Tolstoy and Usdin

for the second mode appears to be in error.) The assumed value 0.25 for Poisson's ratio is probably too small for the surface layer, but the dispersion curves will not be seriously in error as a result, for Press and Ewing (1951) have shown that the dispersion is not greatly different even for a liquid surface layer.

Portions of the dispersion curves for the first and third modes, with Lee's conditions, have been redrawn in Figure 8 in a convenient form for comparison with the observations, and the data of Figure 7 have been plotted for a surface layer of shear velocity 0.75 ft/msec and thickness 4.5 ft. (The group velocity is of course the distance 125 ft divided by the travel-time.) The plots fluctuate about the theoretical first-mode curve but show the same general trend; an explanation of the major fluctuations is offered below. The failure of the Rayleigh wave to emerge earlier than was observed may be attributed to the high-pass filter, which reduced the sensitivity of the receiver by 8 db at 50 cps and by 28 db at 40 cps relative to the value at 60 cps.

The above analysis implies compressional velocities of 1.30 ft/msec in the surface layer and 4.12 ft/msec in the second layer. Considering the assumptions involved, the latter value is not seriously different from the value 5.14 ft/msec deduced from the refraction observations (Figure 2b). The mean thickness of the surface layer between the transducer and the position of the Rayleigh wave observations was given as 4.0 ft by the first-arrival observations of Figure 2a. The standard survey, carried out at a time of year when a greater thickness might have been expected due to lowering of the water-table, gave the rather smaller value 3.8 ft. These values may be compared with the thickness 4.5 ft indicated by the dispersion data. The latter determination is not likely to be much in error from assuming Lee's conditions; for it may be deduced from dispersion curves sketched by Kanai (1951b) that the variation in layer thickness obtained by varying the assumed rigidity contrast from 8.0 to 20.0 would be only about eight percent. The variety of values obtained for the thickness are believed to indicate different actual depths of penetration. The greatest thickness was given by the Rayleigh wave with frequencies around 60 cps , and the least value by the explosive impulse, which had very high frequencies in its onset; while the frequencies in the relevant part of the transducer impulse were intermediate and gave an intermediate value of the thickness. The greater penetrating power of low frequency seismic energy has been studied in detail by Pekeris (1948) for the case of dispersive waves travelling over the sea bottom.

AIR-COUPLED WAVES

A notable feature of Figure 6iii is the high-frequency sinusoidal wave-train superimposed on the first cycle of the dispersive wave. This vibration and also the fluctuations of period in the early part of the dispersive wave may be explained as effects of coupling between the ground and the air. The possibility of such coupling was suggested by Bateman (1938). A detailed study of the phenomenon as it appeared in association with flexural waves in a floating ice-sheet was

published by Press and Ewing (1951a), and the theory has since been extended to the present case of Rayleigh waves in stratified ground (Jardetsky and Press, 1952). The "ground roll" produced by elevated explosions, which are now some-

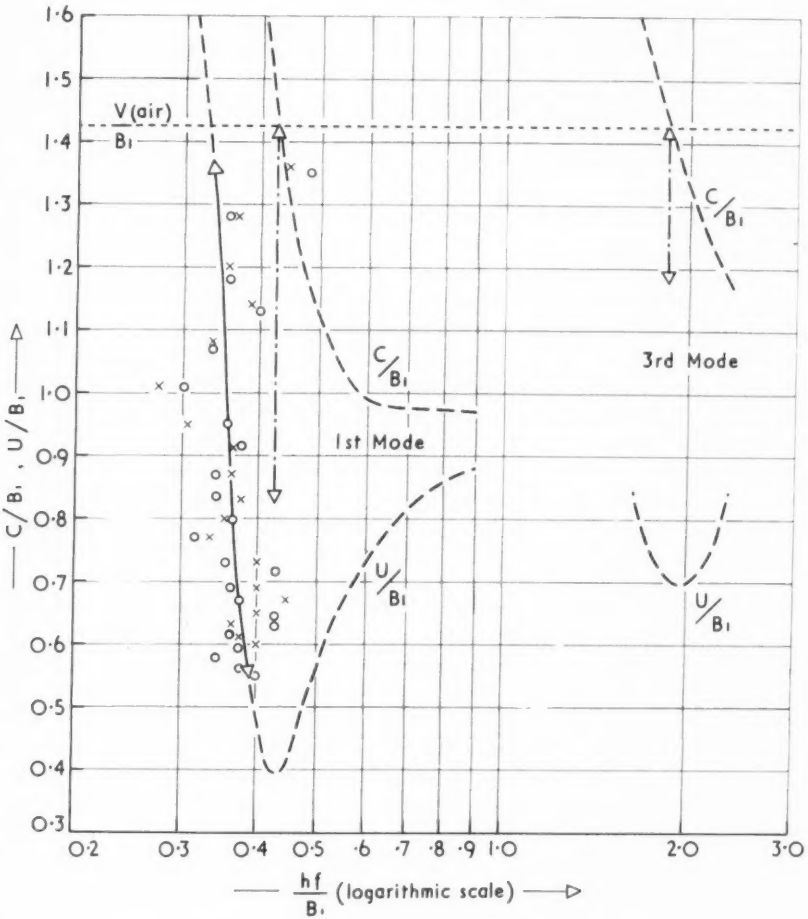

FIG. 8. Frequency/velocity observations plotted against theoretical dispersion curves. × data from Figure 6, i. ○ data from Figure 6, iii.

– – – – – theoretical curves.

⟵——⟶ postulated Rayleigh wave train (see Figure 9).

⟵·–·–·⟶ air coupled wave train (as observed in the 3rd mode, and as postulated in the 1st mode).

C=phase velocity; U=group velocity; B_1=shear velocity of surface layer; h=thickness of surface layer; f=frequency.

times used in seismic prospecting, has been found to be almost entirely due to air-coupling. The phenomenon arises when the phase velocity of a surface wave is very nearly equal to the velocity of airborne sound travelling over the surface; energy is then transferred across the surface in spite of the great disparity of acoustic impedance. Air-coupling is remarkable for setting up a vibration of constant frequency in the vicinity of an impulsive source.

The air-coupled wave in Figure 6iii has a frequency of about 330 cps. Evidently the strength of this frequency in the impulse generated in Figure 6iii, was many times greater than in Figure 6i, where the wave is barely noticeable. In Figure 6v, the wave has been further accentuated by generating an impulse with a spectrum centred near the required frequency. The wave can also be seen in Figure 3, especially at the distances 40 ft and 50 ft. The onset of the wave occurs at 117 msec in Figure 6, i-iv, and at 163 msec in Figure 6v, the latter having been recorded at the distance 175 ft; hence the velocity of the onset was 1.07 ft/msec, a likely value for the velocity of sound in air. The wave also satisfies the other essential condition for air-coupling, for when it is plotted against the dispersion curves of Figure 8, adopting the same surface-layer conditions as for the Rayleigh wave, the onset is found to lie near the curve of phase velocity for the third mode, and if the thickness of the surface layer is taken as 4.2 ft instead of 4.5 ft the onset falls precisely on the curve as shown. (The curve of phase velocity was accurately located at the point where phase velocity equals $\sqrt{2}B_1$, a value for which computation by Newlands' formulae (1952) is exceptionally simple, and which in the present case happened to be very close to the velocity of the airborne sound; otherwise the portions of the third-mode curves shown in Figure 8 were derived from those sketched by Tolstoy and Usdin (1953).) The thickness 4.2 ft is consistent with the values obtained above by other means, and it may be presumed that the Rayleigh wave of frequency 330 cps penetrated to a depth 0.3 ft less than the first mode wave discussed earlier.

Air-coupling to a Rayleigh wave of higher mode than the first has not, as far as the author is aware, been reported before. It would perhaps be surprising to find an air-coupled wave of higher mode and not of the first mode also, when the appropriate frequency exists at the source. Upon closer examination of the data of Figure 7 it appears that much of the distortion noted in the Rayleigh wave may indeed be attributed to a first mode air-coupled wave. In Figure 9 a wave-train resembling that of Figure 6i has been synthesized from a Rayleigh wave and an air-coupled wave. The frequency and phase of the Rayleigh wave were computed by integration of a frequency versus travel-time curve derived, for the distance 125 ft, from the theoretical group velocity curve in Figure 8. The wave has been taken as a cosine function of the integral since travel-times have been reckoned from the peak of the impulse at the source. For the air-coupled wave the theoretical frequency is easily found from Figure 8 to be 70.8 cps; and the phase to be expected from a vertical piston source is opposite to that of the Rayleigh wave. The amplitudes of the two waves have been assumed to vary as shown in Figures 9i and 9ii; Figure 9iii shows that the resultant wave-train then

approximates closely to that recorded, especially when the extraneous high frequencies shown in Figure 6iv are allowed for. Since the conditions adopted for the theoretical dispersion curves were not identical with those at Makara the details of the two components waves cannot be depended on, but their existence and general character appear to be established. Thus, the first mode air-coupled wave is believed to have made a substantial contribution to the wave-train in Figure 6, i, ii, and iii.

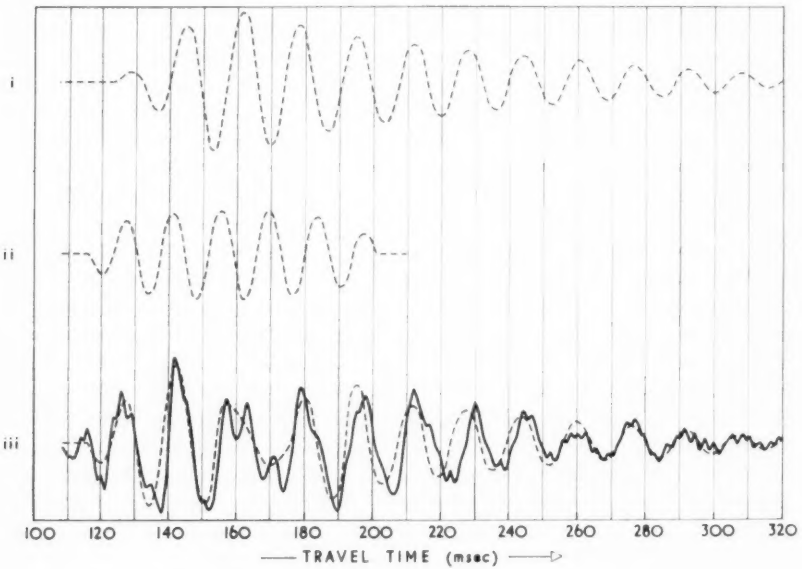

FIG. 9. Comparison of postulated and recorded wave trains.
i postulated Rayleigh wave.
ii postulated air-coupled wave.
iii ——— recorded wave train (traced from Figure 6, i).
iii - - - - - resultant of postulated Rayleigh and air-coupled waves.

The duration and relative amplitude of Rayleigh waves and of associated air-coupled waves have been discussed by Press and Ewing (1951b). In the vibrations detected by a geophone at the surface, the Rayleigh wave predominates for a buried source and the air-coupled wave for an elevated source; but when the phase velocity of a Rayleigh wave approaches the velocity of sound in air, energy is radiated into the air and, as in the present case, the Rayleigh wave becomes highly attenuated. With the transducer at the surface, radiating directly into both ground and air, it was to be expected that both the Rayleigh wave and the air-coupled wave would be generated. A previous instance of an air-coupled wave

and a dispersive wave appearing together occurred during the experiments on ice-sheets mentioned above (Press, Crary, Oliver, and Katz, 1951), with an explosion 1 inch deep in ice 8 inches thick. In the same experiments it was found that air-coupled waves developed satisfactorily in ice of irregular thickness, even where the thickness varied by as much as 50 percent over the path; but although the regular thinning of the surface layer at Makara would not be expected to prevent the development of air-coupled waves it may have affected their duration. Ordinarily an air-coupled wave continues until the arrival of energy that has travelled wholly in the ground at the appropriate Rayleigh-wave group velocity. Both the air-coupled waves at Makara terminated much sooner, as may be seen in Figure 8; hence the latest energy to arrive can have travelled only part of the total distance as a Rayleigh wave, and it is easily calculated that this part amounted to about 35 ft for the first mode and 20 ft for the third mode. Homma (1952) has shown that a Love wave travelling in a layer of uniformly varying thickness retains its general character over a distance proportional to the square root of the wavelength, so that a wave of frequency 70.8 cps would travel about 2.2 times as far as a wave of frequency 330 cps, taking the velocities as equal. Although no direct analogy can be assumed between Love and Rayleigh waves, this ratio is sufficiently close to 1.75, the ratio of the distances calculated above, to suggest a similar cause for the limited duration of the air-coupled waves. Such waves could of course also be limited by absorption in the ground, but the recorded wavetrain as shown in Figure 6iii–v, appears to end rather abruptly, whereas absorption would be expected to produce a gradual decay.

The absence of an identifiable third mode Rayleigh wave at Makara suggests that the vibrator radiated more energy into the air than the ground at the higher frequencies. The vibrations arriving after the air-coupled wave in Figure 6iv have not been positively identified but appear to be impulsive shear waves travelling in the surface layer, followed by a few cycles from the high frequency branch of the first mode Rayleigh wave. There is no definite evidence of the second mode dispersive wave or of an air-coupled wave associated with it. It is known, however, that the even-numbered modes are different in character from the odd-numbered modes. The motion at the surface is progressive elliptical in the former case and retrograde elliptical in the latter (Kanai, 1951a), and Tolstoy and Usdin (1953) have shown that the odd-numbered and even-numbered modes in a surface layer correspond respectively to the symmetric and antisymmetric modes in a free plate. On account of these differences the even-numbered modes are sometimes called Sezawa or M_2 waves, but the distinction has not been made here, following Newlands (1952), since both sets of modes are represented by the same theoretical dispersion equations.

CONCLUSION

The investigation has touched on several of the recent developments in the science of seismic wave propagation. At present, theory is in many respects in

advance of observation, and applied seismology has incorporated only a fraction of existing knowledge. At the same time, much of the theory is fragmentary, having been worked out to explain particular sets of observations. In these circumstances there seems scope for a general study of propagation at shallow levels in the ground, where a wide variety of rock types and formations is to be found and detailed conditions may be determined in advance by drilling and other means. In nature the uniform conditions desirable for such a study are usually confined to rather short distances. But the standard explosive source is least satisfactory at short distances, and its application has been least successful at shallow levels. Consequently, the application of a controlled source to the study of propagation as illustrated above may provide a useful addition to existing experimental techniques.

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THE EFFECT OF TOPOGRAPHY ON NEAR-SURFACE VELOCITIES*

W. BAILLIE† AND T. ROZSA†

ABSTRACT

Fictitious seismic anomalies sometimes result from the use of inadequate techniques in making the surface corrections. The effect of topography on the velocities of the underlying layers, commonly referred to as load effect, is a factor which is generally neglected in routine seismic interpretation. The importance of analyzing the load factor is illustrated by an actual example in which a fairly attractive seismic anomaly is shown to be entirely due to velocity variations associated with surface topography. A method of correcting for load effect is discussed.

INTRODUCTION

It is an established fact that wildcat tests have been drilled on seismic anomalies which are later found to have no geologic significance. Such fictitious anomalies often result from the use of inadequate techniques to correct for the weathered layer, for surface elevation changes, and for unusual velocity gradients.

A consideration which is generally overlooked in routine seismic interpretation, although referred to in the published literature (Krey, 1954; Widess, 1946), is the effect of differential overburden on the velocities of the underlying layers, commonly referred to as load effect.

The purpose of this paper is to illustrate the importance of analyzing the load factor in making a geologic interpretation of the seismic data.

ORIGINAL SEISMIC ANOMALY

Figure 1a is an isotime map of a prospect in the plains area of Western Canada, contoured on a seismic event originating within the Lower Cretaceous section some 6,000 feet below the surface. The seismic anomaly covers a considerable area; however, the indicated structural relief is relatively small. The direction of regional dip is towards the southwest in this area so that the critical reversal is to the north and east. The contouring has been purposely simplified in this paper by omitting all shot points other than those where core hole velocity measurements have been made; however, in all other respects, such as indicated structural relief and lateral extent, the anomaly is the same as mapped by the original seismic survey.

EVALUATION OF THE SEISMIC ANOMALY

Figure 1b is the surface topography map of the same prospect. The low areas along the north and east flanks of this surface feature form part of a drainage

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system. A very marked similarity between the reflection horizon map and the surface topography map is evident at first glance. This coincidence immediately arouses the suspicion that the weathering corrections for those shot points falling along the river valley, where a considerable thickness of gravel is present, are probably in error. This is not the case, however, as penetration to a high speed refractor is indicated at all locations.

The possibility that a buried low velocity layer, which does not register in the

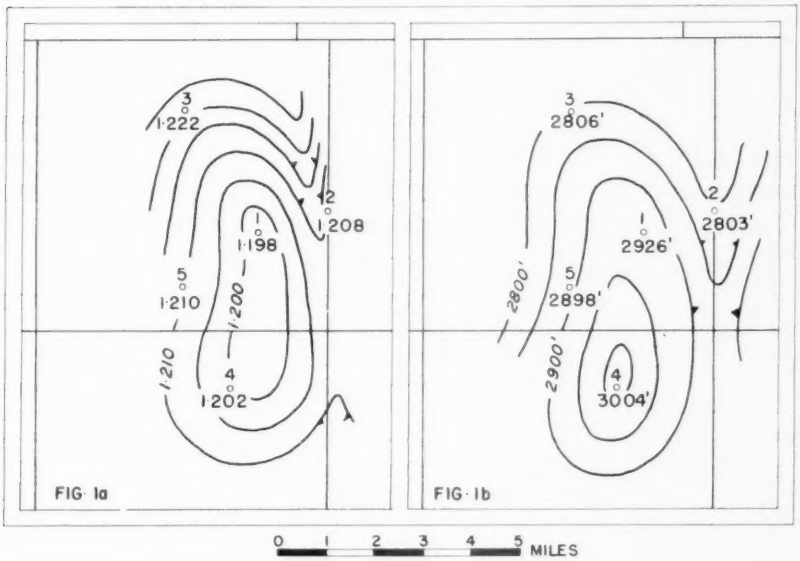

FIG. 1. Comparison of seismic anomaly with surface topography.

refraction first arrivals, might be the source of the anomaly was also considered. To determine if such a layer were present, a series of core hole velocity measurements was made on both the crest and on the north and east flanks of the indicated seismic anomaly. The locations of these core holes are shown by the circles labelled 1 to 5 inclusive on Figure 1.

Extreme care was exercised in making the velocity measurements. A string of charges spaced 50 feet to 100 feet apart on a cable was lowered into each hole and fired progressively from bottom to top. A series of uphole geophones, placed in concentric circles of varying radii, 5 feet, 15 feet, and 25 feet respectively, was used to record the uphole times from the various shot depths.

Referring to Figure 2, the time-depth graphs derived from these surveys demonstrate that no velocity inversions exist. Furthermore, the computed cor-

rections to the datum of 2,700 feet above sea level are found to agree almost perfectly with the measured corrections, the maximum error at any one shot point being .002 second.

EVIDENCE OF LOAD EFFECT

These facts alone would tend to support the assumption that the structural anomaly, as originally mapped, is essentially correct. However, it can be shown that by using the measured seismic travel times to correct to progressively deeper

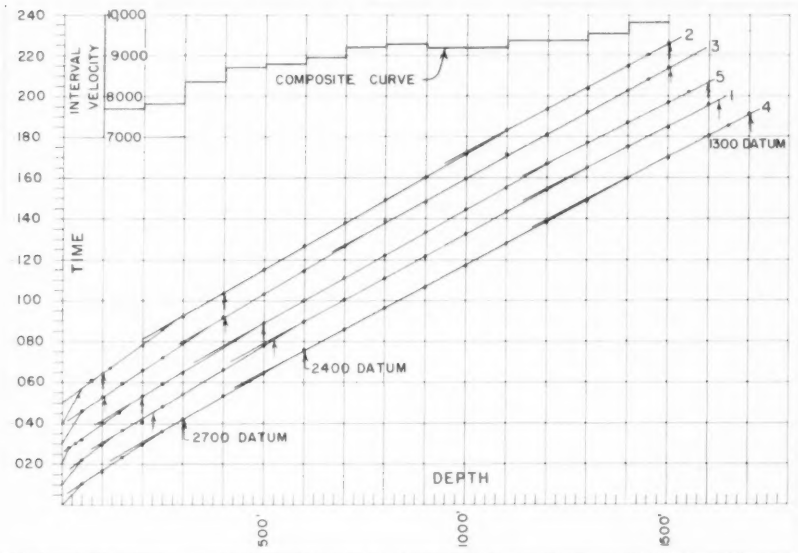

FIG. 2. Time-depth curves. (Note: Each curve is offset progressively by .010 second.)

datum levels the indicated reflection time relief between shot points gradually diminishes.

Table I is a tabulation of the measured seismic travel times for common datum intervals at the various shot points arranged in order of decreasing elevation. These times have been taken directly from the time-depth data illustrated in Figure 2. In Table II the total travel time for the depth interval between the 2,700 datum and the 1,300 datum at each shot point is shown together with its corresponding interval velocity. These data indicate a definite relationship between the interval velocities and the surface elevations, the higher interval velocities being present under higher surface elevations and vice versa. The same relationship of interval velocity and surface elevation is evident at deeper datum intervals. In Table III the time intervals between the 2,400 datum and 1,300 datum at each shot point have been treated as above. In this particular case,

the upper datum line is 403 feet below the surface at the point of lowest elevation and 604 feet below the surface at the point of highest elevation. Since these depths are far below the zone of weathering and any glacial drift cover, it must be concluded that the velocity variation occurs within the consolidated sediments and is not caused by the inclusion of variable thicknesses of low velocity material in the measured intervals.

Referring again to Table I, the interval times for the three deeper datum

TABLE I

HOLE	4	1	5	3	2
ELEVATION	3004'	2926'	2898'	2806'	2803'
2900 - 2800	·0125				
2800 - 2700	·0125	·0120	·0135		
2700 - 2600	·0110	·0115	·0120	·0130	·0140
2600 - 2500	·0115	·0120	·0120	·0130	·0135
2500 - 2400	·0110	·0120	·0120	·0125	·0115
2400 - 2300	·0105	·0110	·0110	·0120	·0110
2300 - 2200	·0105	·0110	·0110	·0115	·0115
2200 - 2100	·0105	·0110	·0115	·0115	·0115
2100 - 2000	·0105	·0105	·0110	·0115	·0110
2000 - 1900	·0105	·0110	·0110	·0110	·0115
1900 - 1800	·0105	·0105	·0110	·0110	·0115
1800 - 1700	·0105	·0110	·0115	·0105	·0110
1700 1600	·0105	·0105	·0105	·0110	·0110
1600 - 1500	·0100	·0100	·0100	·0105	·0105
1500 - 1400	·0105	·0105	·0100	·0110	·0105
1400 - 1300	·0105	·0100	·0100	·0105	·0105

TABLE II

4	1	5	3	2
3004'	2926'	2898'	2806'	2803'
·1485	·1525	·1545	·1605	·1605
9430	9180	9060	8720	8720

TABLE III

4	1	5	3	2
3004'	2926'	2898'	2806'	2803'
·1150	·1170	·1185	·1220	·1215
9560	9400	9280	9020	9050

TABLE I. INTERVAL TIMES FOR COMMON DATUM INTERVALS

TABLES II. INTERVAL TIMES AND VELOCITIES
2,700 Datum—1,300 Datum

TABLE III. INTERVAL TIMES AND VELOCITIES
2,400 Datum—1,300 Datum

intervals are practically constant regardless of the surface elevation. It can therefore be concluded that the effect of topography on the velocity gradients in the underlying layers has disappeared at these greater depths. A graphical illustration of the variation in travel times between the 2,700 datum and progresssively deeper datum planes is shown in Figure 3. The two-way seismic travel times between the 2,700 datum and deeper datum planes have been plotted opposite the surface elevation of each shot point. The lines drawn through each set of time values

bring out the variations of interval time with elevation for progressively greater depth intervals. The general inclination of these lines appears to increase progressively with depth to about the 1,500 datum level, and then remains constant for the datum levels below. The change in inclination is brought out more clearly by the curve in the lower part of Figure 3. The difference in two-way travel time at each datum level for a surface elevation change from 2,800 feet to 3,000 feet, i.e., the time inclination of the datum line, is plotted directly below the datum

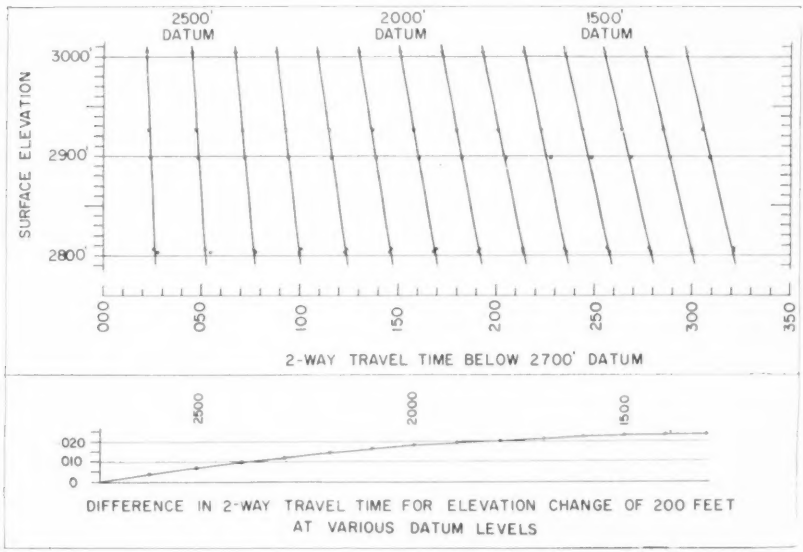

FIG. 3. Progressive variation of travel times below a horizontal datum associated with differential surface elevation.

line in question. The line joining the plotted points forms a smooth curve which shows that the inclination gradually increases to about the 1,500 datum level and then becomes constant.

From these data it must be concluded that the entire topographic or load effect has disappeared at the 1,500 datum level.

Figure 4 shows a comparison between the contoured reflection times adjusted to the 2,700 datum level and the contoured reflection times after adjusting to the 1,400 datum level. The seismic anomaly entirely disappears, leaving only regional dip after the correction for topographic effect has been applied.

The above example demonstrates conclusively the importance of analyzing the effect of topography on the velocities of the underlying layers. In this particular case, the topographic relief is only of moderate magnitude yet its effect

on the near surface velocities is sufficient to create a fictitious structural anomaly.

Generally speaking, load effect signifies an upwarping of the near surface velocity layers under topographic highs due to an excess of overburden. There is, however, some justification for believing that the change in attitude of the velocity layers might actually result from a negative de-loading process rather than a positive loading effect. The net result is the same; however, the cause is exactly opposite. According to the latter theory, the sedimentary layers attain a velocity which is dependent on composition, compaction, depth, and time of burial, etc.

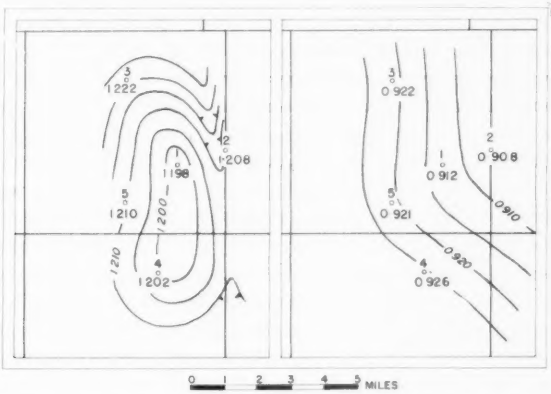

FIG. 4. Comparison of seismic anomalies before and after correcting for load effect.

The release in confining pressure resulting from differential erosion tends to differentially lower the near-surface velocities in accordance with surface topography.

Experiments to date have shown that the measured topographic effect on near-surface velocities is usually greater in those areas where the near-surface sedimentary velocities are higher and the sediments are more highly indurated than in areas where the opposite is true. Secondly, in areas where considerable and variable thicknesses of glacial drift are present, the velocity variations in the near-surface layers occasionally appear to be more closely related to the relief at the top of the consolidated sediments rather than relief at the topographic surface. It is possible that the elapsed time since the last glacial period is not sufficient to allow for a complete re-adjustment of the velocity gradients to conform to the present topographic surface.

METHODS OF CORRECTING SEISMIC DATA

Because of the wide variation in the magnitude of the topographic effect from place to place, it is necessary to make a local analysis for each area in which seismic surveys are being conducted. Figure 3 can be used as a correction chart

for topographic effect to adjust the reflection time values for other shot points within the control area. In order to adjust the reflection times to the 1,400 datum level, the two-way time correction is found on this particular curve opposite the surface elevation of the shot point in question. Provided that the originally computed corrections to the 2,700 datum are within the required limits of accuracy, the additional correction between this datum and the 1,400 datum will remove the topographic effect on the travel times through the deeper layers and properly adjust the data to the 1,400 datum.

Another method has also been devised by which the appropriate correction velocity to compensate for the topographic effect can be determined. This is accomplished by making velocity measurements in a number of holes, strategically located both on topographic highs and lows, and drilled to a common datum level. The interval time from either a constant depth below the surface or, depending on the nature of the area, from the base of the glacial layer to the deepest common datum is plotted against its corresponding depth interval at each location. The best fitting line through the plotted points is a measure of the velocity required to compensate for topographic effect. Where the topographic effect is severe, the indicated correction velocity will be considerably higher than the highest velocity measured by the velocity surveys.

In Figure 5 the interval times for the zone between 50 feet below the surface and the 1,400 datum, and the zone between 200 feet below the surface and the same datum are plotted against their corresponding depth intervals. All times have been read directly from the time-depth curves shown in Figure 2. The best fitting line through each set of data indicates the correction velocity required to compensate for the combined load effect and elevation differential. These velocities are found to be 15,500 feet per second for the greater interval and 14,750 for the smaller interval. In other words, to correct from a depth of only 50 feet

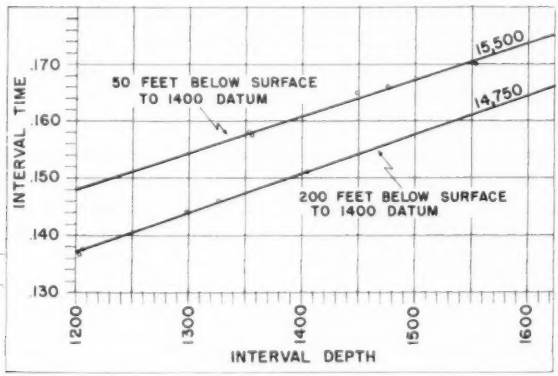

FIG. 5. Apparent correction velocity.

below surface to datum requires a higher velocity than needed to correct from 200 feet below surface to datum. The difference is due to the topographic effect on the travel time through the intermediate 150 feet of section. According to the interval velocity curve of Figure 2, which is a composite curve for the five surveys, the highest velocity encountered is of the order of 9,800 feet per second, yet the indicated correction velocities are 15,500 feet per second and 14,750 feet per second respectively.

Table IV is a tabulation of the differential corrections computed from the velocities determined in the above manner and the actual corrections obtained directly from the time-depth graphs.

The first comparison shows the computed two-way elevation correction using a velocity of 15,500 feet per second compared to the measured two-way differential correction for the interval between 50 feet below the surface and the 1,400 datum. A constant amount of 0.150 second has been subtracted from each of the interval times to adjust the two sets of values to the same order of magnitude.

The second set of figures compares the computed two-way correction using a velocity of 14,750 feet per second to the measured two-way interval time between 200 feet below the surface and the 1,400 datum. In this case, a constant of 0.130 second has been subtracted from each of the measured interval times. The closer agreement between computed and measured corrections for the deeper interval is probably due to the fact that velocity variations caused by other surface phenomena and not by topographic effect alone are not completely eliminated at a depth of 50 feet below the surface.

From these data, it is evident that in order to compute the proper reflection time differences between shot points in areas where the surface topography has affected the velocities of the near-surface formations, it may be necessary to use

TABLE IV

HOLE NUMBER	4	1	5	3	2
ELEVATION	3004	2926	2898	2806	2803
ORIGINAL DATUM	2700	2700	2700	2700	2700
DIFF. IN ELEVATION	304	226	198	106	103
TIME 1400 DATUM	·1805	·1780	·1770	·1735	·1750
TIME AT 50 FEET	·0105	·0120	·0120	·0160	·0170
TIME AT 200 FEET	·0295	·0320	·0330	·0360	·0385
2T (50' TO DATUM-K)	·040	·032	·030	·015	·016
$\frac{2 \text{ (DIFF. IN ELEV.)}}{15500}$	·039	·029	·026	·014	·013
2T (200' TO DATUM-K)	·042	·032	·028	·015	·013
$\frac{2 \text{ (DIFF. IN ELEV.)}}{14750}$	·041	·031	·027	·014	·014

TABLE IV. COMPARISON OF MEASURED CORRECTION TIMES AND COMPUTED CORRECTION TIMES

a considerably higher correction velocity than is actually encountered in the zone in which the topographic effect persists. The percentage increase in velocity required to compensate for topographic effect varies from area to area and should be determined by actual measurements.

It should be noted that consideration must be given to the location of the velocity surveys so that any regional velocity gradient, if present, will not confuse the determination of the appropriate correction velocity. The effect of the regional velocity gradient, which may continue with depth throughout the entire sedimentary section, is usually handled as a separate correction.

CONCLUSIONS

The example described in this paper demonstrates that the effect of topography on the velocities of the underlying sedimentary layers is a factor which should be considered before the seismic data can be properly processed. The importance of acquiring reliable near-surface velocity measurements to supplement conventional seismic surveys is gradually being recognized throughout the industry.

By making studies of this nature, a better ratio between successful completions and failures for tests drilled on seismic anomalies should be attained.

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GEOPHYSICS, VOL. XXI, NO. 4 (OCTOBER, 1956), PP. 969-991, 23 FIGS.

CHARACTERISTICS OF EXPLOSIVES FOR MARINE SEISMIC EXPLORATION*

J. J. JAKOSKY† AND JOHN JAKOSKY, JR.‡

ABSTRACT

This paper describes the results of preliminary studies which were conducted at San Diego, California early in 1953, and detailed large scale field tests conducted during the later months of 1953 and the early part of 1954, chiefly near Santa Barbara, California. These studies are part of an investigation to develop an explosive which would overcome some of the disadvantages of black powder, which now is the only explosive permissible for offshore exploration in California.

Special instrumentation was developed for recording the pressure-time curves from underwater explosions.

The predominant characteristics of these curves have been related to seismic record quality and the destruction of fishes and other marine life. The experimental studies have shown that non-lethal explosives are available which will give record quality and operating costs comparable to the conventional dynamites and which are superior to the black powders.

CREATING THE SEISMIC WAVE

A considerable amount of energy is required to create the seismic disturbance necessary to produce usable reflections in marine exploration, because of the generally low signal/noise ratio prevailing in the California offshore areas. To date the dynamites have proved to be particularly effective, and the most practical source for this energy. Unfortunately, however, when a conventional charge of dynamite is detonated under water it creates a very sharp shock with an abrupt wave front. A steep wave front, unless of very low amplitude, will be lethal to many species of fish, especially those with an air bladder. Most of the more valuable food and game species of fish have this biological structure.

HISTORY OF OFFSHORE EXPLORATION IN CALIFORNIA

The initial seismic work off the coast of California was conducted during 1948 and 1949, and employed dynamite as the source of seismic energy. Charges of 40 to 80 pounds were quite commonly required due to the high noise level, and the poor performance characteristics of the instruments employed at that time. Because of the large quantity of fish killed during the early work (Fitch and Young, 1948), the state permits governing seismic operation were revoked in 1949, largely due to political pressure by the sport and commercial fishing interests.

In 1951 studies for a substitute explosive were initiated by one of the oil companies (Fry and Cox, 1954; Hubbs and Rechnitzer, 1952). These studies

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again confirmed experimentally that any concentrated charge of dynamite produced the steep wave front lethal to marine life. It was found that even with the charges jetted well into the bottom sediments, excessive fishkill occurred.

Additional tests were conducted using other types of explosives, and finally it was found that black powder had a very low fish kill and gave a usable seismic record. The record, when compared with one made with only nine pounds of dynamite, was of poor quality. After extensive tests in many areas with relatively minor fish kill, the use of black powder was officially approved by the California Department of Fish and Game in September 1951 with a maximum allowable charge of 90 pounds per shot. Since that date black powder has been the only explosive legally approved for marine exploration. The standard procedure is to shoot the maximum charge of 90 pounds which generally gives a record of about one to two seconds duration.

During 1953 a total of 4,533,080 pounds of black powder were shot with an observed kill of 2,057 fish (Calif. Fish and Game). The legal necessity of using black powder has thrown a very heavy financial burden upon the offshore exploration program. The 90 pound charge of black powder delivered at the shotpoint costs about $30.00, while a nine pound charge of dynamite, giving an equivalent or better record, costs about $3.00. From the viewpoint of conservation of fish, desirable progress has been made. From a strictly economic viewpoint, however, this progress has been made at a large increase in the cost of explosives and a greatly increased hazard due to the handling of black powder.

EFFECTS OF EXPLOSIONS ON FISH

The general criteria for evaluating the effects of an explosion on fish are fairly well established from previous work by others. One of the early papers dealing with such studies was published in 1947 by J. A. Aplin of the California Fish and Game Commission. Shortly afterwards, a paper by John E. Fitch and Parke H. Young (1948) also of the California Fish and Game Commission, gave the results of additional studies, and the following paragraphs are taken directly from that paper:

"The damage that occurs to fish life is, at the present time, thought to be largely limited to those species possessing an air bladder. Post mortem examinations of a large number of fish, recovered from both the surface and from the ocean floor, show similar effects. Invariably there is (an outward) rupture of the air bladder, and, depending upon the distance and position of the fish in relation to an explosion, other parts of the viscera may be damaged or crushed." . . . "However, when the fish does not possess an air bladder, controlled experiments (Aplin, 1947) showed that there was no noticeable effect. . . .

"There is, in each species of fish, an inherent resistance to shock pressure. Some species, as the barracuda, kingfish, queen-fish and others, possess a tough, heavy-walled air bladder and a body of cylindrical proportions. Such fish appear to have much more resistance to pressure than do laterally compressed fish with a very thin-walled air bladder, such as the salt-water perch. Jack smelt, although

cylindrical in shape, have a thin air bladder and are quite susceptible to blasts. The various rockfishes, which are also quite susceptible, are good examples of fish that have large air bladders with medium thick walls."

Susceptibility among Fish

"It has been observed many times that not all of the fish within the lethal range of the exploded charge are killed or even outwardly affected by the concussion. Several times in the kelp beds (Santa Barbara area) when a charge was exploded, small perch (*Brachyistius frenatus*) spun and gyrated crazily in the water whereupon kelp bass (*Paralabrax clathratus*), evidently attracted by these flashing cripples, began feeding upon them and in a few minutes the area was spotted with feeding kelp bass. Succeeding shots in the same area resulted in the death of some of these bass, but, regardless of this, the feeding activities of those unharmed continued."

In their paper, Fitch and Young also report on some studies of the ocean bottom made by their divers, which indicated that the number of fish killed which do not float, is negligible when compared to the number that are killed and that come to the surface.

From published data, therefore, it is believed that the species of fish killed by explosions are chiefly those with air bladders, and a preponderance of these fish rise to the surface when killed. The fish and other marine life without air bladders are seldom affected by the explosions.

DESIRED CHARACTERISTICS OF SHOCK WAVES

The optimum shock wave for marine exploration would have one set of characteristics for its biological effects, and another set of characteristics for its seismic effects. The biological characteristics will keep the pressure below a few atmospheres positive and always above one atmosphere negative. The seismic characteristics will require that the shock wave have sufficient energy to produce reflections of great enough amplitude to allow a workable signal/noise ratio, and also that it have a wave front only sufficiently steep to give the necessary resolving power. Fortunately, these two sets of characteristics overlap within a somewhat narrow range suitable for seismic exploration.

During our experimental studies, many different explosives and configurations of explosives or shaped charges were studied. Space will not permit a full description of these studies, but typical pressure waves from a few explosives will be discussed to show how the explosion wave may be modified to give the desired characteristics.

RECORDING OF PRESSURE WAVES

The general schematic arrangement of equipment for recording the pressure waves is shown in Figure 1 and consists essentially of a pressure sensitive gauge or hydrophone, whose signal was fed into an amplifier and transducing circuit, and thence to a dual beam oscilloscope. The sweep of the oscilloscope traces was

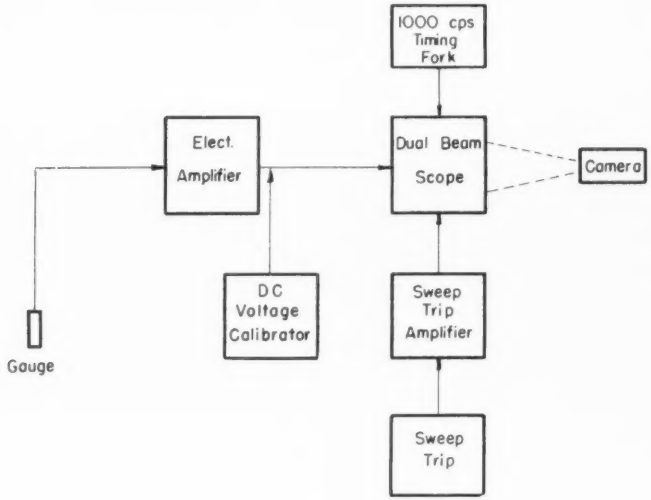


FIG. 1. Block diagram of recording equipment.

started by the signal from the trip geophone submerged under the surface of the water.

A view of the complete pressure recording equipment as mounted aboard one of our boats is shown in Figure 2.

The wave paths while recording the pressures are shown by the diagram in Figure 3. The direct wave traveled from the explosive charge to the trip geophone and the pressure sensitive element, over the direct path AB. The trip geophone is placed a few feet in front of the pressure element to start the sweep of the oscilloscope beam about one or two milliseconds ahead of the arrival of the wave at the pressure element.

It will be seen that another portion of the shock wave will travel the path ACB, undergoing a reflection at the water-air interface C. The reflected wave from the water-air interface has a negative pressure or rarefaction. This negative pressure can rise to that value where the water tension equals the absolute pressure. When negative values in excess of absolute zero are created, the water mass is pulled apart, forming holes or "cavitation." Examination of the pressure time curves, in this paper, will show that this reflected wave or cutoff reaches its expected normal value of 15 pounds negative pressure.

EQUIPMENT FOR RECORDING PRESSURE WAVES

In order to record both the peak pressure and the actual wave shapes, a modified Rutishauser type displacement gauge was used instead of the conven-

FIG. 2. Complete pressure recording equipment mounted on the recording boat.

tional integrating piezo-electric crystal type, as utilized by many previous investigators (Silverman, 1943), (Cole, 1948). In the present instrumentation, the pressure sensitive element comprised a flat, thin walled diaphragm positioned parallel to an insulated surface element, and having a known electrostatic capacity therewith. The capacity between the diaphragm and the element, and the inductance of the matching transformer, form a parallel resonant circuit, oscillating at approximately 12 megacycles per second. Any deflection of the diaphragm caused by change in hydrostatic pressure against it, changes the electrostatic capacity, thereby changing the frequency of the circuit. The change in frequency shows as a change in output voltage of the resonant circuit. Calibration of the gauge was accomplished by applying a series of different hydrostatic pressures. Recalibration

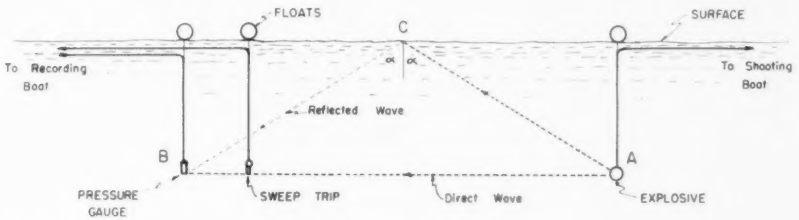


FIG. 3. Pressure curve paths through water.

of the gauge, after completion of the experimental studies, checked within a fraction of one percent with the initial calibration at the start of the work, and gave a good check on satisfactory equipment performance.

Pressure-time records were made by photographing the face of the dual beam oscilloscope tube, as shown by Figure 4. Two sweep rates employed, the upper

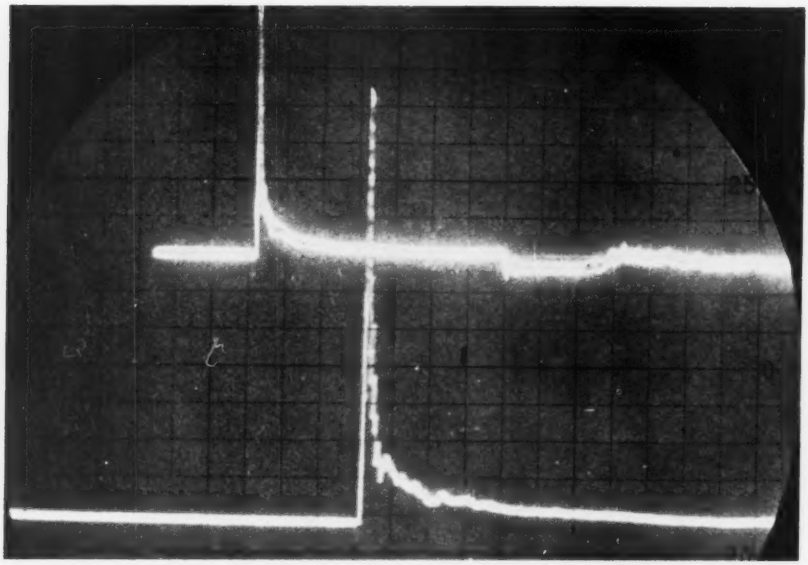


FIG. 4. Typical pressure curve as photographed on face of dual-beam cathode ray tube from a one pound charge of 40 percent dynamite.

curve having a sweep rate of one millisecond per division; and the lower curve having a sweep rate of $\frac{1}{5}$ millisecond per division. Pressures were measured by the vertical displacement of the beam above or below the ambient axis, and during these tests the calibration was 38 pounds per square inch, per vertical division.

Figure 4 shows a typical pressure wave from a one pound charge of 40 percent dynamite. The pressure sensitive element was positioned at a depth of six feet, and was 25 feet away from the charge. The abrupt and almost instantaneous rise in pressure shown by the curve is caused by the extremely steep front of the pressure wave. The high positive pressure, which in this case is over 440 pounds per square inch at the 25 foot distance, generally will be lethal to fish within a radius of about 150 feet. In addition, this high positive pressure wave will, upon reflection at the water-air interface, undergo a 180° reversal in phase and become a negative pressure wave producing cavitation in the water. This negative pressure

wave is particularly damaging to fish because it ruptures their swim bladders and blood vessels, and often may burst the abdominal cavity itself.

The killing power of the rarefaction wave is greatest near the air-water interface. The intensity of the rarefaction wave decreases with depth due to (1) geometrical attenuation and (2) by cancellation of the negative pressure by the increase in hydrostatic pressure. At about 30 foot depth, the hydrostatic pressure is approximately 15 pounds positive, which theoretically cancels the maximum negative pressure that can be created during cavitation. This theory explains why there seldom is damage to fish from negative pressures, at depths approaching 30 feet of water, or deeper.

The presently-used black powder has a characteristic pressure curve of the general type shown in Figure 5. This is the curve recorded 50 feet from a conventional 45 pound can of black powder with 6 feet of primacord, fired with a number eight blasting cap, when positioned at a depth of six feet. The peak pressure is approximately 21 psi, and extends over a period of about six milliseconds. The resolving power of the seismic energy from the black powder is relatively low, especially in areas of thin-bedded sedimentaries. Black powder creates a preponderance of low frequency energy which accounts for its moderate pressure rise, and also largely for its decreased lethal properties. As previously mentioned, 90 pounds of black powder are required to give reflections from a depth compara-

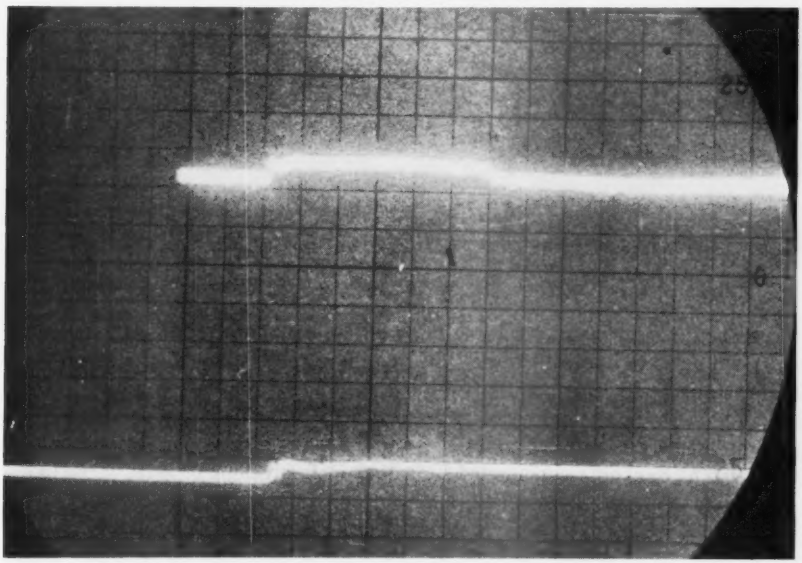


FIG. 5. Pressure curve from 45 pounds of black powder.

ble to those obtained by use of about nine pounds of dynamite in California offshore areas.

One of the reasons why black powder has a low efficiency when used in marine seismic exploration is due to the fact that it must be fired at such a shallow depth in the water. A greater head of water would increase the confinement and improve the efficiency, but generally this can be done only at the expense of creating the so-called "bubble effect." Figure 6 shows the curve obtained at a distance of 25 feet from 19 pounds of black powder under moderate confinement. The area under this curve is equal approximately to that of 45 pounds of the same powder

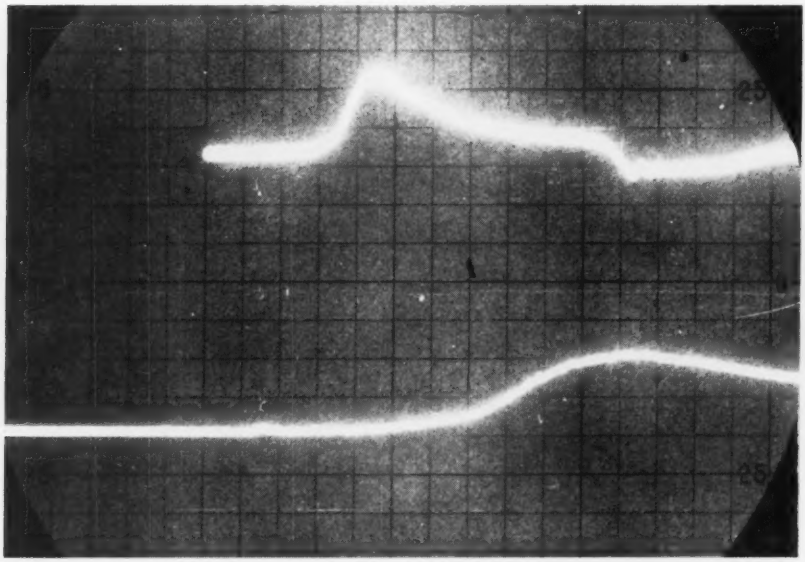


FIG. 6. Pressure curve from 19 pounds of black powder under moderate confinement.

fired without confinement, resulting in more than double the efficiency. One difficulty with this technique is the cost of providing and loading the containers.

Illustrative of another way of modifying the wave shape of an explosive is the curve obtained when a high velocity material like dynamite is surrounded by an envelope of shock-absorbing material. Figure 7 shows a curve from five pounds of 60 percent dynamite surrounded by a four inch envelope of loam earth in a waterproof, rubberized canvas bag, as recorded at a distance of 100 feet and fired at a depth of six feet. The peak pressure at that distance was 132 psi, extending over an interval of 0.4 millisecond. In order to lengthen sufficiently the over-all time of the pulse and to decrease further its peak pressure, the shock-absorbing envelope will need be of such large size as to make it too large and heavy for practical exploration.

All of the experimental work indicated that the higher-velocity gelatins or dynamites were the most desirable materials from the viewpoint of low cost, ease and safety of handling, and high energy content per pound. Considerable effort, therefore, was devoted to a study of methods which would produce the desired modification of their wave shape.

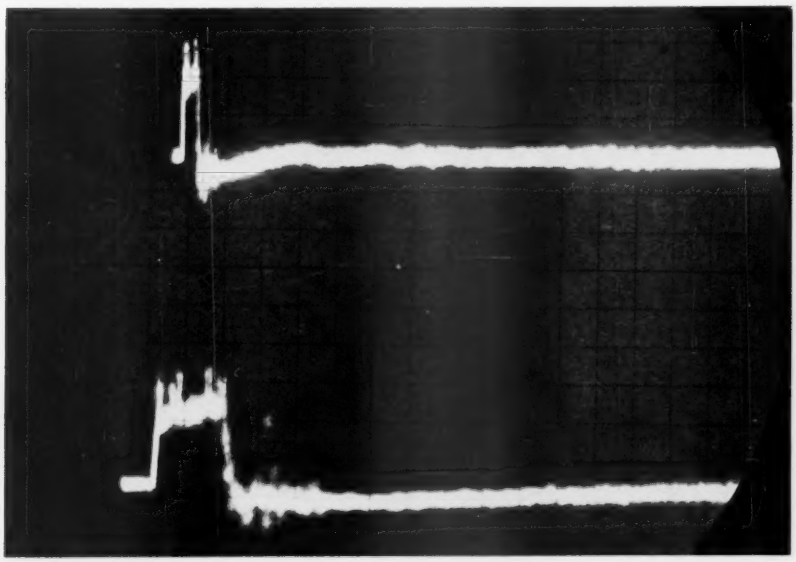


FIG. 7. Pressure curve from 5 pounds of 60 percent dynamite surrounded by an envelope of shock-absorbing material.

One of the initial endeavors was to try a multiple shotpoint arrangement wherein a multiplicity of small charges were positioned in a horizontal plane. Tests were made with a nine-pattern charge suspended from a wooden, 25 foot equilateral triangle lying horizontally on the surface of the water. Each charge was detonated with a number eight cap. All nine caps were connected in series and fired simultaneously. Directly under the triangle, this arrangement gave a steep-front pressure wave quite comparable to that created by a single charge of dynamite as shown in Figure 4. The pressure wave to the side of the triangle varied in complexity depending upon whether the pressure unit was positioned along a line perpendicular to one of the sides, or bisected one of the angles of the triangle. Figure 8 shows a typical pressure curve when the pressure unit is positioned a distance of 100 feet from the nine-point multiple charge of .555 pound each; a total of five pounds. This arrangement was particularly lethal to fish off to the sides, as well as directly underneath the triangle. The physical size of the triangle makes it difficult to handle in any type of continuous shooting program.

A few tests were made using much longer dimensions along the sides of an equilateral triangle to obtain cancellation of the horizontal waves. The charges were each suspended from individual balloons held in position with a light manila line, using three strain boats pulling at each apex of the triangle. Somewhat better cancellation of the horizontal pressure wave components was effected with the larger spacings, but the difficulty of laying out this arrangement, even in a smooth sea, precluded its practical use and further tests were abandoned.

A number of tests were made with various types of shaped charges, generally

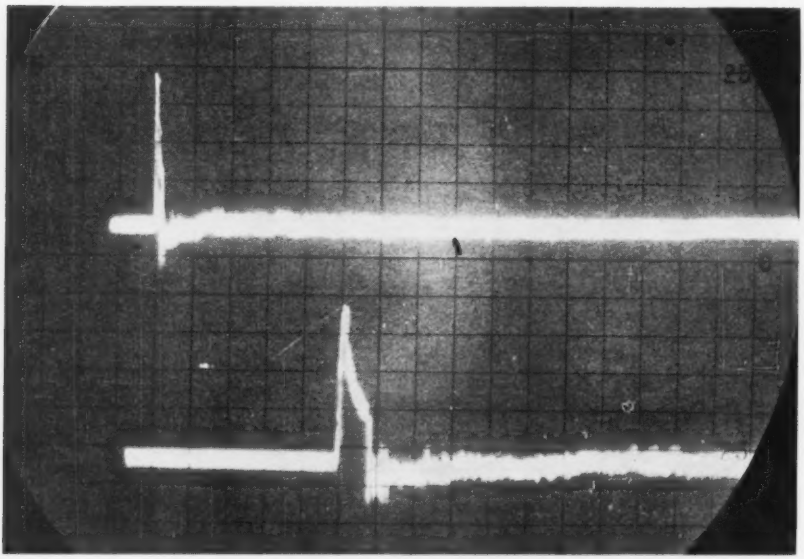


FIG. 8. Pressure curve from nine-point pattern charge.

formed by winding parallel strands of primacord over iron frames of the required shape. Figure 9 shows the frame for a double-cone test, and Figure 10 shows the frame for a spherically shaped charge. Figure 11 is the pressure curve at 100 feet distance, for a five pound cone of primacord, suspended vertically, with the cap and apex at the bottom. The tests with all of the shaped charges were most disappointing and produced none of the results hopefully expected.

One successful technique was that of controlling the rate of reaction; that is, by slowing down the over-all velocity of detonation. This was accomplished by subdividing the charge into a series of small pellets, as shown in Figure 12, and firing them progressively. The first pellet at one end of the string was fired; the shock wave from this pellet then traveled through the water to the next pellet in line and fired it, and a continuation of this process resulted in a series of small explosions or pulses, each spaced a few microseconds apart with a periodicity of

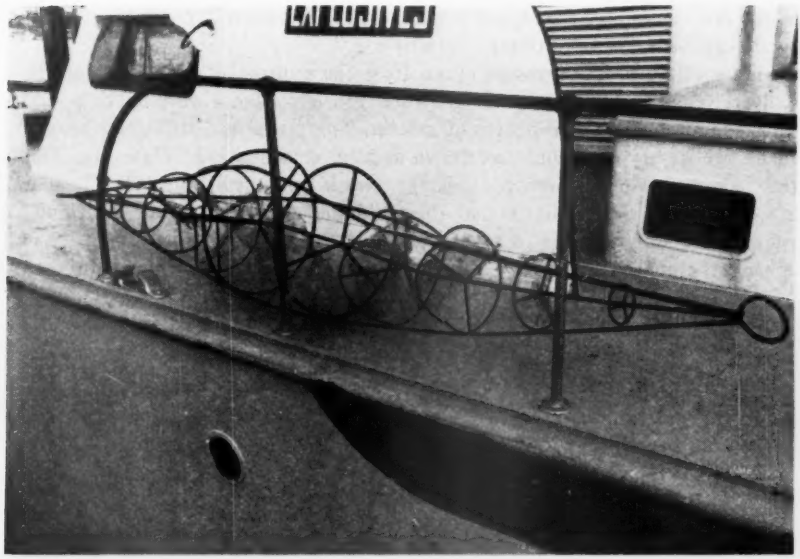


FIG. 9. Iron frame for double cone-shaped primacord charge.

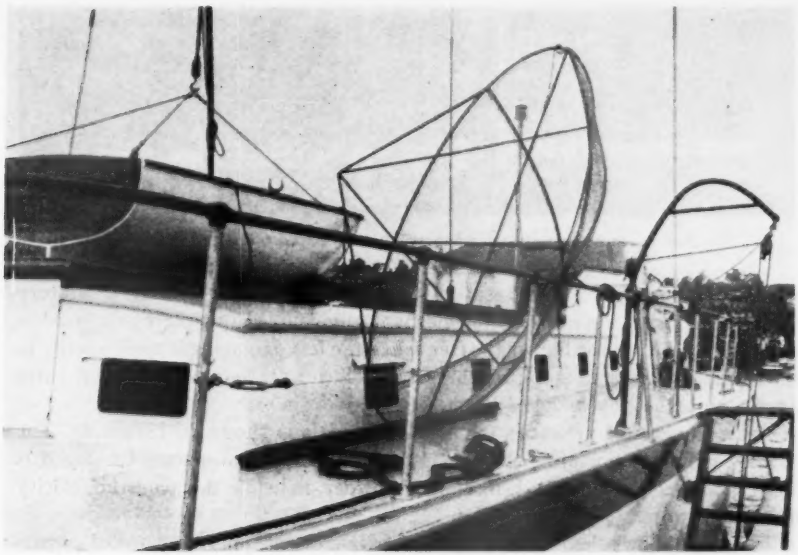


FIG. 10. Iron frame for spherically-shaped primacord charge.

about 5,000 cycles per second, and extending over the desired time interval. This type of explosion has been termed "multipulse."

Figure 13 shows the pressure curve from the multipulse explosive material finally developed. This curve was recorded 100 feet from a vertical 10 pound string containing 50 small pellets of gelatin. The pressure distribution around this charge is very directional, as shown in polar coordinates in Figure 14. This arrangement produced improved seismic records with negligible fish kill. The data obtained to date indicate that the non-lethal properties of the multipulse explosive probably are due to two factors: (1) the relatively small quantity of explosive detonated in each of the individual pulses, and (2) the high peri-

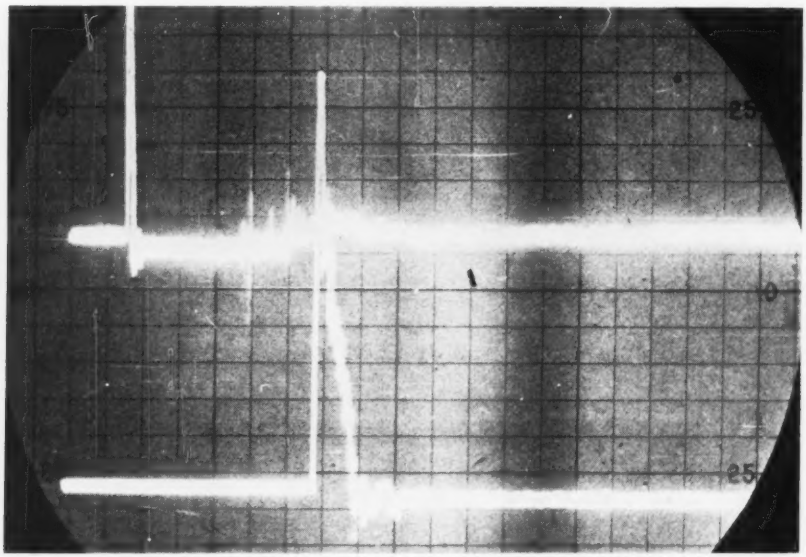


FIG. 11. Pressure curve from five pound cone-shaped primacord charge.

odicity or frequency at which these individual pulses follow each other. Laboratory experiments, using a sonic vibrator mechanically coupled to a plate immersed in water, indicate that the higher the frequency the less damaging is sonic energy to fishes, and at frequencies approaching 5,000 cycles per second, and over, there appears to be no physiological effect.

A comparison of velocities for a few materials is shown in Figure 15. The effective over-all velocity of the multipulse material, at the spacing employed, is about 4,000 feet/second, and, like black powder, is below the acoustic velocity of sound in water.

Figure 16 shows the computed pressure-time curves for 10 pounds of 40 percent gelatin, 10 pounds of the multipulse charge, and 90 pounds of black powder;

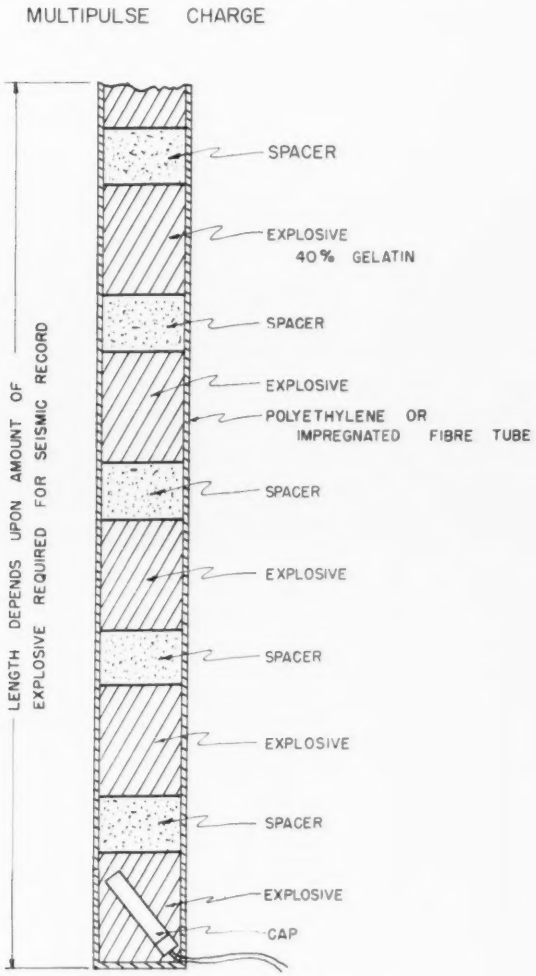


FIG. 12. Pressure curve from pellet charge

all values being computed to the same base at 100 feet distance, to allow direct comparisons.

SEISMIC TESTS

Upon completion of the pressure wave studies near San Diego and Santa Barbara, a marine crew was moved to an off-shore area near Santa Barbara in order to obtain a comparison of records made with the conventional black pow-

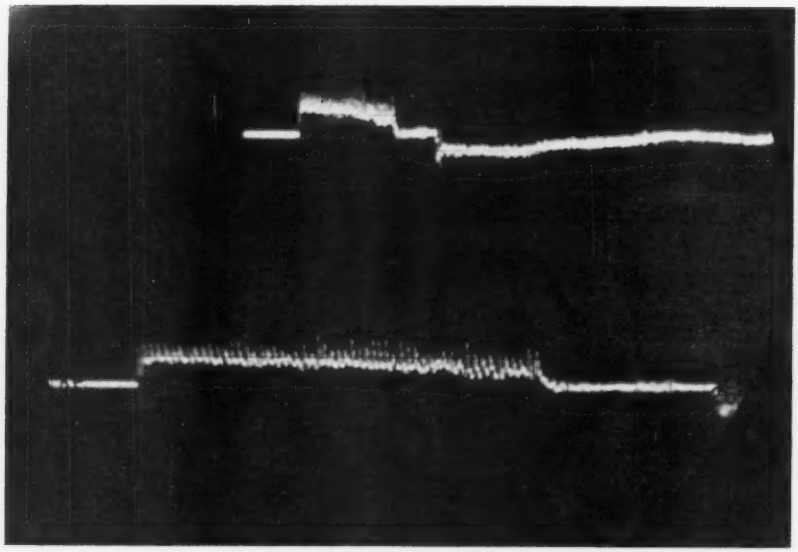
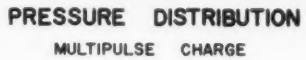


FIG. 13. Pressure curve from multipulse charge.



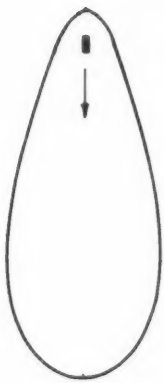


FIG. 14. Pressure distribution surrounding multipulse charge.

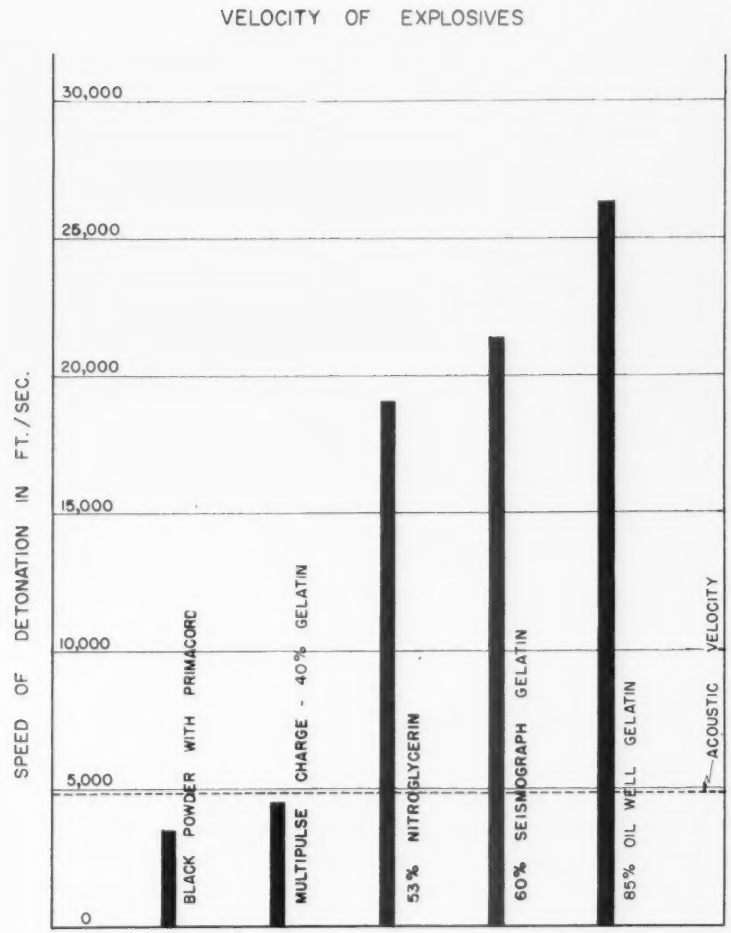


FIG. 15. A comparison of explosive velocities for various materials.

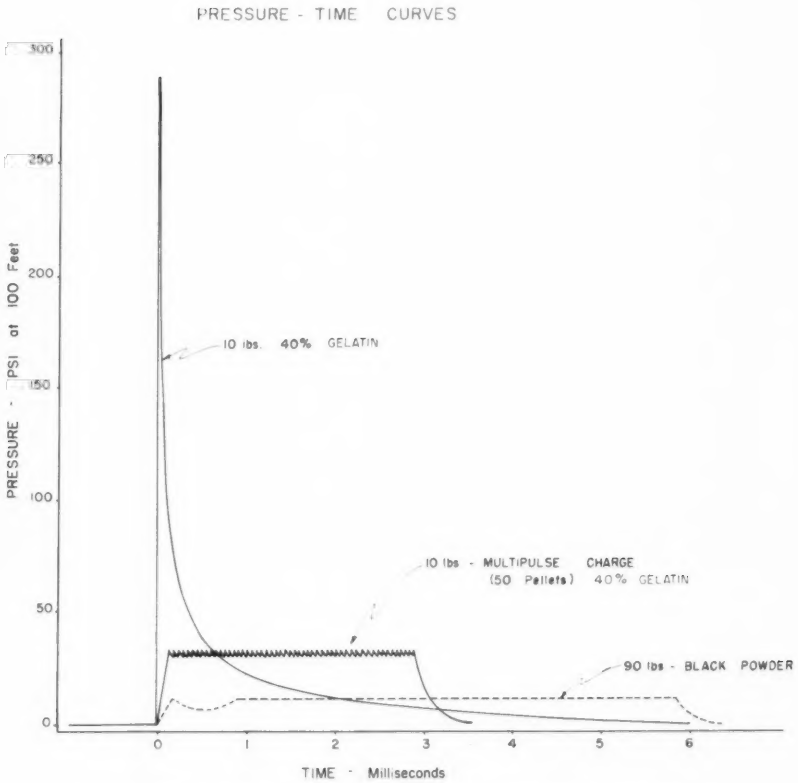


FIG. 16. Pressure time curves for ten pounds of 40 percent gelatin, ten pounds of multipulse and 90 pounds of black powder, computed to the same base.

der charges and multipulse charges, under actual operating conditions. This part of the program covered a total of 125 miles of traverses.

The seismic instrumentation was of the conventional type, using 24 recording traces. Due to the steep dips in the area, the cables were arranged in an "L" spread, to allow resolving of dips to obtain true dip and strike components. The "in-line" cable had a spread of approximately 1,000 feet, two geophones per trace and 12 recording traces. The "wing" cable had approximately an 800 foot spread, with one geophone per trace and 12 recording traces (Fig. 17).

The angle between the two cables of the L spread was measured by sextant, and the bearing of the stern cable was measured by a pelorus, at the time of each shot (Fig. 18).

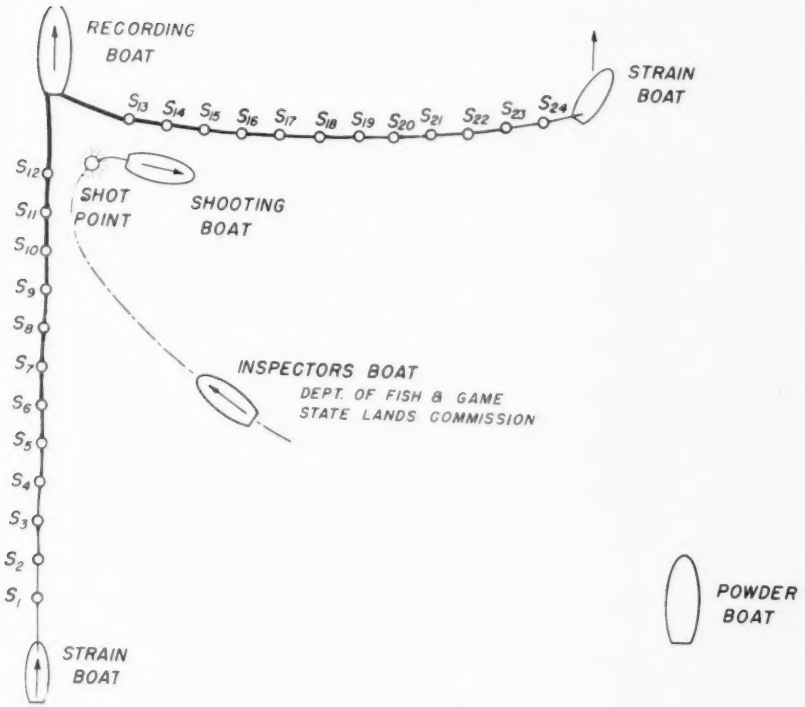


FIG. 17. Geophone cable layout.

To determine the location of the shotpoints the surveying was conducted by a conventional Shoran system. This method of radio surveying gives two range distances, and a "fix" or location is made at the time of each shot.

RECORD QUALITY

The relative quality of the seismic records obtained with the multipulse charge and the black powder is shown in Figures 19 and 20. These records are representative segments of two traverse lines and are typical of the results that were obtained. The traverse lines, from which these records were taken, were shot by alternately using 90 pounds of black powder and a nine to ten pound charge of the multipulse on succeeding shots along the line. The records have been labelled showing which explosive material was used; "B" for black powder and "M" for multipulse. As will be noted, the multipulse charges gave greater depth penetration and generally better quality records. On a few experimental shots,

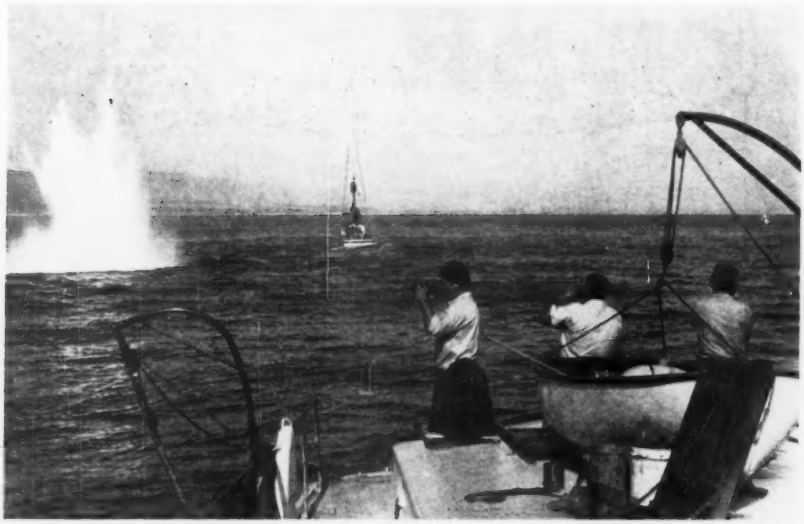


FIG. 18. Measuring the angle between recording cables at time of shot by means of a pelorus.

increased depth penetration was obtained by using somewhat larger quantities of explosives, but regular use was not permissible due to the permit regulations under which the experimental work was conducted.

WATER DISTURBANCE

Figure 21 shows the water plume resulting from the conventional 90 pounds of black powder. The geyser produced by the powder charge rises to a height of 250 feet or more and can be seen and heard for miles. The psychological effect of this geyser no doubt is one of the chief factors contributing to the public opposition to offshore seismic exploration along the West Coast. Figure 22 shows the plume from a ten pound multipulse charge. The water spray thrown up rises to perhaps 30 to 40 feet, and is seldom seen or heard more than $\frac{1}{4}$ mile. Figure 23 shows the two 45 pound cans of black powder for conventional shooting, and a nine pound string of the multipulse material.

CONCLUSIONS

The results of this research program were satisfactory, and explosives were developed which can be employed more advantageously than the presently-approved black powder charges. These explosives will minimize damage to fish and other marine life, and decrease the present hazards of handling, transporting and storing. At the same time a decrease in the cost of explosives to about 1/10 that of black powder could be expected.

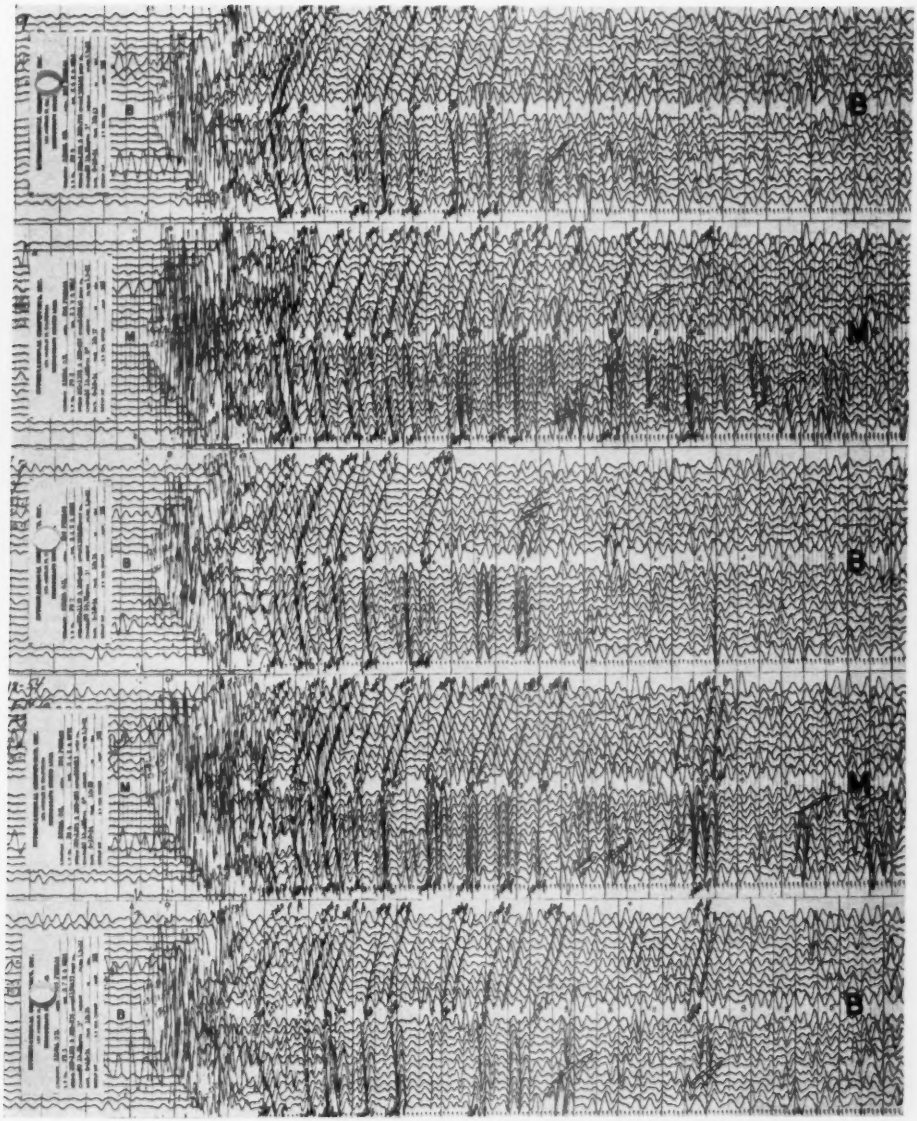


FIG. 19. Comparative record quality obtained by alternate shots of black powder and multipulse along a traverse line. Records labelled "B" for black powder and "M" for multipulse.

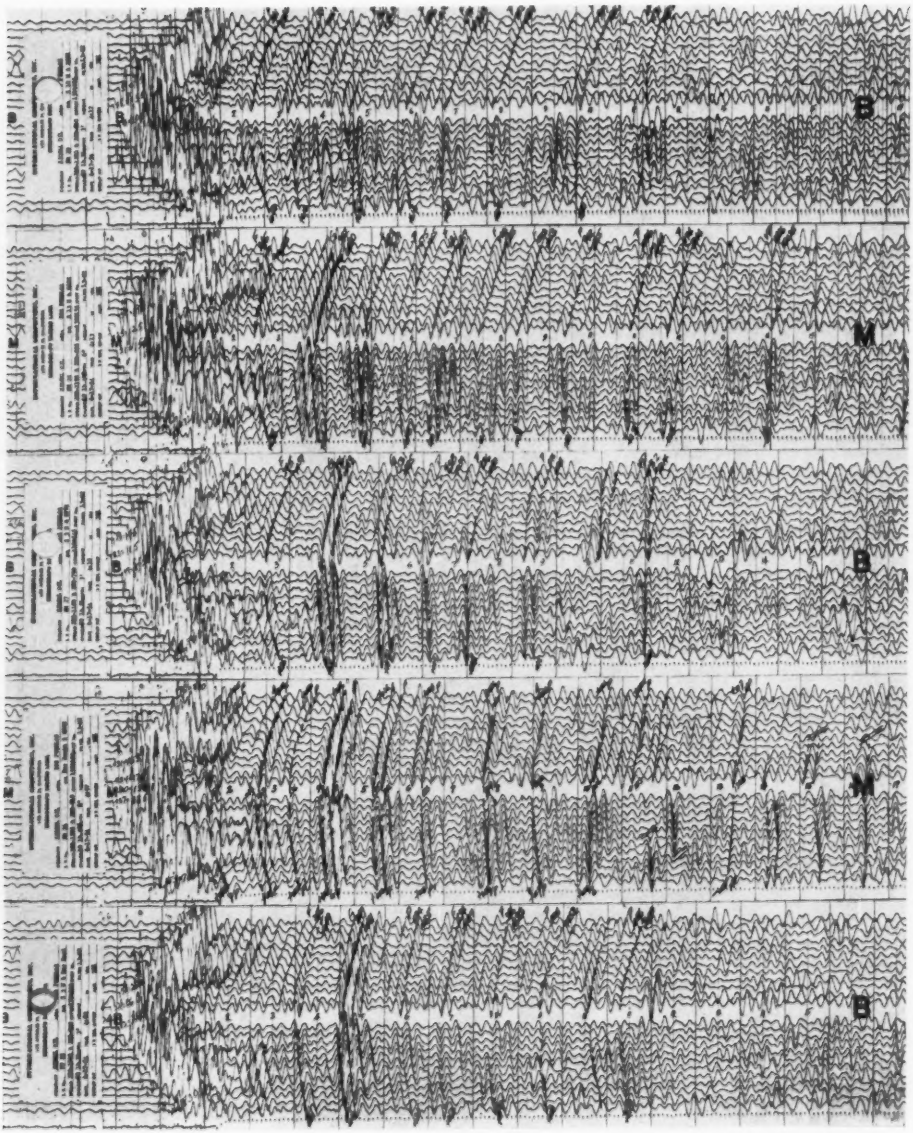


FIG. 20. Comparative record quality obtained by alternate shots of black powder and multipulse along a traverse line. Records labelled "B" for black powder and "M" for multipulse.

FIG. 21. Water plume resulting from conventional 90 pounds of black powder.

FIG. 22. Water plume resulting from ten pounds of multipulse charge.

FIG. 23. Two 45 pound cans of black powder used for conventional shooting and a nine pound string of multipulse material.

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RELATION BETWEEN REFLECTION TIME INCREMENT, INCLINATION OF REFLECTING LAYER AND INTEGRATION COVERAGE*

BERNARD GRUNEBAUM†

ABSTRACT

The purpose of this paper is the establishment of a criterion to ascertain the amount of compositing (or integration) which may be applied to a sequence of seismic traces without producing distortion or cancellation. The subject has been treated primarily from the standpoint of weight dropping technique, but it applies unchanged to standard seismic procedures. The mathematical treatment is based on certain restrictive assumptions which, it is believed, are sufficiently approximate for the purpose intended.

INTRODUCTION

During recent years, a new instrumental technique for processing seismic records has grown in importance, namely the "integration" or "compositing" method, consisting essentially of adding several consecutive seismic traces, previously corrected for such factors as the difference in elevation between either the recording points or the points where the seismic disturbance is generated and the uphole time (only in the case when dynamite is exploded under the ground), to reinforce geophysical signals and eliminate noise. The principal limitation as to the number of traces that can be composited, is the time displacement of the reflection from one trace to the next, a quantity which we have designated by the name of reflection time increment. It may have many causes but the principal one is inclination of the reflecting layer. Furthermore, we must consider that the principal correction of those applied before compositing is that which we call the stepout time correction, which takes care of the distance between the theoretical recording point and the location of the seismic perturbation.

STEPOUT TIME CORRECTION

In the interpretation of our data, we suppose that the arrival times of a reflection, measured on different traces, are the same, if the stepout time correction has been applied and if the reflecting layer is horizontal. Now, the simplest way of calculating the stepout time correction is to assume a horizontal reflection layer. In practice, this method is used only where we expect that it is sufficiently precise; but for the purpose of this paper, we shall assume that this is the standard procedure. Therefore, if the reflection layer is not horizontal, the corrected arrival times of a reflection will change from trace to trace. We shall designate by time increment the change of corrected reflection time, measured for a certain hori-

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zontal coverage and not necessarily between consecutive traces. We want the relationship between this time increment and the corresponding inclination α of the reflecting layer. Also, we want to know to what extent these time incremented reflections remain undistorted during the process of integration. For the moment, an arbitrary velocity distribution is assumed to calculate the depth, but the rays are supposed to be straight lines.

Reference is made to Figure 1. We suppose that $AC=x$ is the horizontal surface coverage. We shall designate by dropping-points the points where seismic disturbances are generated because, when the McCollum Geograph is used, these are the points where the weight hits the ground. Thus, C is the dropping-point corresponding to the first trace, and A the dropping-point corresponding to the last trace, if seismic disturbances are to be generated between A and C. In conventional seismic work, C would be the position of the farthest geophone of the line and A would be the geophone closest to the explosion point. Back to the

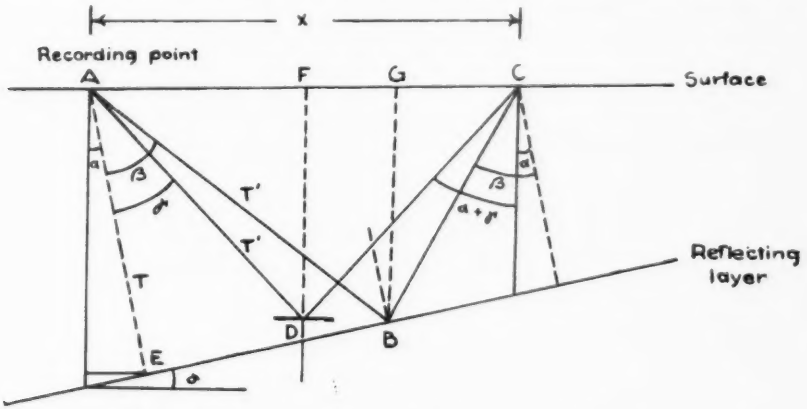

FIG. 1. Straight ray geometry of a reflection from an inclined layer.

Geograph way of thinking, we also suppose, for simplicity, that A is at the same time the permanent recording point. If ΔT is the time increment between the first and the last trace, we desire a relation between ΔT, x and α.

If: Δt = conventional stepout time correction for wave path CBA;

T' = time CBA;

T = time AEA

then, by definition, $\Delta T = T-(T'-\Delta t)$.

Now, to illustrate the stepout time correction, we have a point D located so that:

$$\text{time } CDA = \text{time } CBA = T'$$

and lying on the midnormal to AC. Therefore, for the measured time T', D

would be the reflection point if we had no inclination. Then, by definition

$$\Delta t = T' - T_{FDF}$$

Substituting in the expression for ΔT:

$$\Delta T = T - T_{FDF}$$

The arbitrary velocity distribution function ϕ will be defined by

$$T_v/2 = \phi(z)$$

where:

T_v = two way vertical time and

z = depth.

Using this function, we have

$$T_{AD} = \frac{\phi(z_D)}{\cos(\alpha + \gamma)} = \frac{T_{FDF}}{2\cos(\alpha + \gamma)} = T'/2$$

Hence

$$T_{FDF} = T' \cos(\alpha + \gamma)$$

Substituting in the expression for ΔT, we obtain:

$$\Delta T = T - T' \cos(\alpha + \gamma). \tag{1}$$

T' is obtained easily from geometrical considerations:

$$T' = T_{CB} + T_{BA} = T_{BG}/\cos(\beta - \alpha) + T_{BG}/\cos(\beta + \alpha)$$

with

$$T_{BG} = \phi(z_B)$$

and

$$z_B = AB \cdot \cos(\beta + \alpha) = AE \cdot \cos(\beta + \alpha)/\cos\beta$$

Substituting in the expression for T':

$$T' = [1/\cos(\beta - \alpha) + 1/\cos(\beta + \alpha)]\phi\{AE \cdot \cos(\beta + \alpha)/\cos\beta\}.$$

Similarly

$$x = AB \cdot \sin(\beta + \alpha) + BC \cdot \sin(\beta - \alpha),$$

which, with a few trigonometric transformations, takes the form:

$$x = 2 \cdot AE \cdot \sin\beta/\cos(\beta - \alpha).$$

Therefore the argument of ϕ becomes

$$\frac{AE \cdot \cos(\beta + \alpha)}{\cos\beta} = \frac{x \cdot \cos(\beta - \alpha) \cdot \cos(\beta + \alpha)}{2 \cdot \sin\beta \cdot \cos\beta} = x \cdot \frac{\cos^2\beta - \sin^2\alpha}{\sin^2\beta}$$

Substituting in the expression for T', we obtain

$$T' = [1/\cos(\beta - \alpha) + 1/\cos(\beta + \alpha)]\phi\left(x \cdot \frac{\cos^2\beta - \sin^2\alpha}{\sin^2\beta}\right),$$

or, applying some trigonometric transformations to the function's factor:

$$T' = 2 \cdot \frac{\cos\alpha \cdot \cos\beta}{\cos^2\beta - \sin^2\alpha} \cdot \phi\left(x \cdot \frac{\cos^2\beta - \sin^2\alpha}{\sin^2\beta}\right). \tag{2}$$

We can now substitute T' in expression (1) and we obtain an expression for ΔT which still contains two undesired parameters, namely β and γ. Therefore, we need two more additional relations to eliminate them. The first relation is given by the condition for the location of point D, namely

$$\phi(z_D) = \tfrac{1}{2}T' \cos(\alpha + \gamma)$$

but

$$z_D = \tfrac{1}{2}x \cdot \cot(\alpha + \gamma) \quad (x/2 = AF = FC).$$

Therefore:

$$\phi\left\{\frac{x}{2}\cot(\alpha + \gamma)\right\} = \frac{T'}{2}\cos(\alpha + \gamma).$$

For the second relation, we must consider the wave path AEA:

$$T_{AE} = \phi(z_E)/\cos\alpha = T/2 \quad \text{with} \quad AE = z_E/\cos\alpha.$$

Therefore

$$\phi(AE \cdot \cos\alpha) = \frac{T}{2}\cos\alpha,$$

and replacing AE by its expression as a function of x, we obtain:

$$\phi\left\{\frac{x}{2}\,\frac{\cos\alpha \cdot \cos(\beta - \alpha)}{\sin\beta}\right\} = \frac{T}{2}\cos\alpha. \tag{4}$$

Expressions, (1), (2), (3) and (4) solve our problem, at least theoretically with the approximation of straight line rays: (4) gives β; substituting β in (2) we obtain T'; substituting T' in (3) we obtain γ; substituting both T' and γ in (1) we obtain the desired relation between ΔT, x and α.

Unfortunately, even for relatively simple velocity distributions, the analytical problems in performing the calculations just outlined, are rather complex.

Let us consider the case most commonly specified, that of average velocity increasing linearly with time:

$$\text{Average velocity} = v_0 = a + bt_v = a + bT_v/2$$

where t_v and T_v are respectively one and two-way vertical time and a and b are numerical constants. This is equivalent to:

$$\text{Interval velocity} = v = a + 2bt_v = a + bT_v, \quad \text{and}$$

$$T_v/2 = \phi(z) = \frac{a}{2b}\left(-1 + \sqrt{1 + 4bz/a^2}\right)$$

as can be easily verified. The solution of expression (4) is:

$$\cot \beta = \frac{1}{x}\left(aT/\cos \alpha + bT^2/2\right) - \tan \alpha.$$

Now, assuming T' known, (3) reduces to:

$$\sin^4(\alpha + \gamma) - \left(1 - \frac{4a^2}{b^2T'^2}\right)\sin^2(\alpha + \gamma) - \frac{8xa}{b^2T'^2}\sin(\alpha + \gamma) + \left[\frac{2x}{bT'^2}\right]^2 = 0$$

We see that in the proposed case, the exact solution of our problem is impractical for routine work.

In the utmost simplified case of constant velocity, we obtain:

$$v = \text{constant}$$

$$T_v/2 = \phi(z) = z/v$$

$$\cot \beta = \frac{vT}{x \cos \alpha} - \tan \alpha$$

$$T' = \frac{x \cos \alpha}{v \sin \beta}$$

$$\sin(\alpha + \gamma) = \sin \beta/\cos \alpha \quad \text{and finally}$$

$$\Delta T = T - \left(T^2 - \frac{2xT}{v}\sin \alpha\right)^{1/2} \quad \text{which rearranged gives}$$

$$\sin \alpha = \frac{2T \cdot \Delta T - (\Delta T)^2}{\frac{2xT}{v}}$$

and neglecting $(\Delta T)^2$, we obtain finally

$$\sin \alpha = \frac{v}{x}\Delta T.$$

To apply this formula, it is useful to remember that if:

y = fraction of one wavelength;
λ = wavelength,

we have:

$$\Delta T = y\lambda/v = \frac{y}{v}\,\frac{v}{f} = y/f \quad (f \text{ is frequency}).$$

This last expression for sin α could have been obtained by much simpler considerations and in fact, has been used already to a certain extent. But we must not forget that it is a very rough approximation and our analysis shows that it is based on the following assumptions:

a. straight ray path;
b. constant velocity;
c. $(\Delta T)^2$ negligible.

In a numerical example that we have worked out, with a typical Gulf Coast velocity distribution,[1] the horizontal coverage being about 14/9 times the depth and the inclination about 11°, these assumptions produced an inclination error of 4 percent.

INTEGRATION OF SINUSOIDAL WAVES

Suppose now that we have a continuous reflection, with a measurable time increment for a given horizontal coverage. This value is used as a measure of the dip and therefore, during the process of integration, the continuity and amount of time increment must remain unchanged. Obviously, this is possible only if the specific time increment $\Delta T/x$ (time increment per unit horizontal coverage) is smaller than a certain limiting value. We shall consider that the unit of horizontal coverage is the distance between the first and the last drop point (or similarly the distance between the nearest and the farthest geophone in conventional work) included in one integration. Thus, if r is the distance between consecutive drop points,

$$x = (n - 1)r$$

where n is the number of drops (or geophones) included in one integration.

For the sake of simplicity, we suppose that we are integrating identical waves, perfectly sinusoidal and of constant amplitude, differing only in a constant amount of phase shift δT between consecutive traces. If A is an arbitrary and constant amplitude factor, then we write the amplitude s of the first wave of the group to be integrated, in the form:

$$s_1 = A \sin 2\pi f T$$

f being the mean, average or simply the highest energy level frequency of our band. The second wave will be:

$$s_2 = A \sin 2\pi f(T - \delta T)$$

[1] A constant average velocity was used.

and so on. The last wave to be integrated will be:

$$s_n = A \sin 2\pi f[T - (n-1)\delta T]$$

The integrated wave will have an amplitude equal or proportional to

$$s_0 = \frac{1}{n}\sum_{i=1}^{n} s_i = \frac{A}{n}\sum_{i=0}^{n-1} \sin 2\pi f(T - i\delta T)$$

with the condition:

$$(n-1)\delta T = \Delta T$$

Now, if n is sufficiently large and δT sufficiently small, we have:

$$\delta T \sum_{i=0}^{n-1} \sin 2\pi f(T - i\delta T) = \int_{T-\Delta T}^{T} \sin 2\pi f T \cdot dT$$

Then, for our purposes, we may consider the following expression as valid:

$$\sum_{i=0}^{n-1} \sin 2\pi f(T - i\delta T) = \frac{n-1}{\Delta T}\int_{T-\Delta T}^{T} \sin 2\pi f T \cdot dT$$

$$= \frac{n-1}{2\pi f \Delta T}\left[\cos 2\pi f(T - \Delta T) - \cos 2\pi f T\right]$$

Hence

$$s_0 = \frac{(n-1)A}{2\pi f n \cdot \Delta T}\left[\cos 2\pi f(T - \Delta T) - \cos 2\pi f T\right]$$

By expressing ΔT in fractions y of a period, we get:

$$s_0 = \frac{(n-1)A}{2\pi n y}\left[\cos (2\pi f T - 2\pi y) - \cos 2\pi f T\right] \tag{5}$$

Now we discuss this relation.

For $y=1$ (one complete period phase shift between first and last trace), s_0 is identically zero for all values of T. Therefore, as y approaches 1 (from lower values than 1 as we shall see), the reflections tend to vanish because of the integration process. For $y=\frac{1}{2}$, we obtain:

$$s_0 = -\frac{(n-1)A}{n}\,\frac{2}{\pi}\cos 2\pi f T = \frac{(n-1)A}{n}\,\frac{2}{\pi}\sin (2\pi f T + \pi/2).$$

which means that there is no reason to believe that for one half period phase shift, the signal will be destroyed by integration. According to equation (5), the sinusoidal character of the waves is evidently preserved through integration, for any value of y. Comparing the expressions of the original and the integrated

wave, we see that the reflection will be phase shifted as a whole, producing an error in reflection time and therefore in depth. We designate this phenomenon by the name of parallel phase migration. It will be studied later.

In our daily routine, we have found quite a number of geophysicists who were quite surprised about these results. We have concluded that it seems to be a more or less conventional belief that integration over more than $\frac{1}{4}$ or $\frac{1}{2}$ period time increment has to be detrimental to any signal. With the purpose of showing that this is false, we have prepared another less mathematical way to arrive, at least qualitatively, at the same results.

Reference is made to Figure 2 where we have drawn a series of identical sine waves with a constant phase shift between consecutive traces. To examine the case where we expect that s_0 is identially zero, we take $y=0.9167=1-1/12$, $(n=13,\ n-1=12)$; that is, if any 13 consecutive traces are taken, the first one

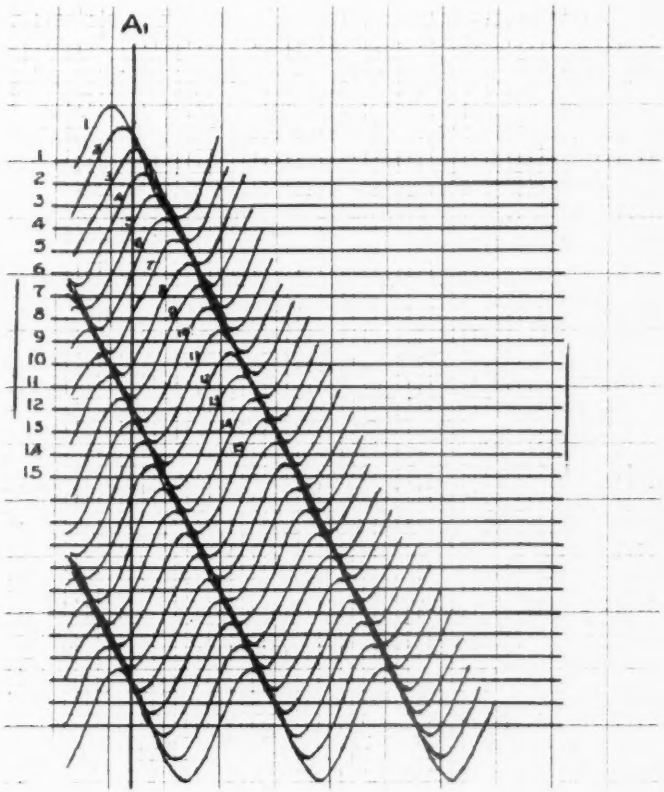

FIG. 2. Sinusoidal waves with constant time increment between consecutive traces.

and the last one are exactly one wavelength out of phase. y is not taken equal to 1 as indicated by theory, because expression (5) was deduced under the ideal condition of n approaching infinity or very large and in our present case, $n=13$. Thus, for the value of y that we have chosen, we must integrate any 12 consecutive traces of Figure 2. Let us suppose that we are integrating traces No. 1 to No. 12 both included, on an arbitrary time line A_1. Looking at our figure, we see that trace No. 1 cancels with No. 7, trace No. 2 cancels with No. 8 and so on until trace No. 6 cancels with No. 12. Adding all together, the result is obviously zero. Thus, we have proven graphically one of the consequences of expression (5).

In the same way, let us investigate now the case $y=\frac{1}{2}$. Actually, because n is not infinite, we have to take $y=0.5833$ in our case. With reference to Figure 2 again, we must integrate traces 1 to 7, both included. We see that this integration is zero only, if it is performed on a time line containing either a maximum or a minimum of trace No. 1. If we integrate on the arbitrary time line A_1, then trace No. 1 will cancel trace No. 7, but all other traces will contribute to a value different from zero.

Actually, from a strictly analytical standpoint, the integrated waves are always different from zero except when $y=1$. For different reasons, one of them being the construction of the electronic integrator, values of y greater than 1 must be discarded because of heavy distortion and loss of signal-to-noise ratio which makes the signal unrecognizable except on no-noise laboratory records.

Back to analytical reasoning, let us investigate now the amplitude of the integrated wave. We obtain from (5):

$$\frac{ds_0}{dT} = \frac{(n-1)A}{2\pi ny}\left[-2\pi f \sin(2\pi fT - 2\pi y) + 2\pi f \sin 2\pi fT\right]$$

equating to zero and assuming y different from zero, we obtain

$$T = \frac{1}{4f}(2m - 1 + 2y)$$

where $m=1, 2, 3, \cdots$. From previous considerations, we know that y must be always smaller than 1; thus $m=1$ and

$$T = \frac{1}{4f}(1 + 2y).$$

Substituting this value in (5), we obtain the amplitude of the integrated wave, s_{max} as

$$s_{max} = \frac{n-1}{n} A \frac{\sin \pi y}{\pi y}$$

Remembering that A is the amplitude of the basic waves, we see that when y approaches zero, s_{max} approaches A; that is, the integrated wave will have the

same signal-to-noise ratio as the basic waves if integration has not weakened the noise at all. For $y=\frac{1}{2}$, we obtain:

$$s_{max} = \frac{2}{\pi} A = 0.64A$$

which means that the amplification of the signal is 64 percent of the **MAXIMUM** amplification of the noise (assuming no cancellation), a situation which we believe, is always acceptable. It is a known fact that integration weakens the noise and therefore, we still can expect that the signal-to-noise ratio will be improved, even when $y=\frac{1}{2}$ or greater.

We shall introduce now the arbitrary convention, based mostly on the writer's experience, that with integration, the maximum possible loss of signal-to-noise ratio and the distortion due to background noise are both acceptable, when the amplification of the signal is 50 percent or more of the maximum amplification of the noise. This gives a limiting value y_0 of y, defined by:

$$\frac{\sin \pi y_0}{\pi y_0} = 0.5$$

with the condition that $0.5 < y_0 < 1$. Solving, we find $y_0 = 0.603$ which means that we recommend that integrations be performed only when y is smaller than 0.6.

We are very conservative in assigning a maximum value of 0.6 to y. Actually, at $y=0.6$ the signal-to-noise ratio decreases 50 percent *only* if all the noise waves are in phase. But as we know, they are not and this is precisely what distinguishes a geophysical signal from noise. In other words, the fact that our integration technique permits differentiation between a signal and noise with the aid of phase relations alone (when the energy level becomes very low) represents the principal and definite advantage of our instruments over conventional layouts. Therefore, disregarding the effect of phase relations, the integration has a natural tendency to improve the signal-to-noise ratio which overcompensates the effect of phase relations unless we are in the vicinity of $y=1$. Under normal conditions, field experience and laboratory experiments have shown, that relatively distortionless reproduction can be expected even for phase differences as high as 0.8.

To find the approximate maximum inclination of reflecting layers, α_m, that can be handled under these conditions, the following formula can be used:

$$\sin \alpha_m = \frac{v}{x} \frac{y_0}{f} = \frac{v}{x} \frac{0.6}{f} \tag{7}$$

where:

v = average velocity;
x = horizontal surface coverage;
f = frequency.

PARALLEL PHASE MIGRATION

We shall now evaluate the phenomenon of parallel phase migration previously described. The investigation shows, as we shall see, that under the conventions which we have accepted as standard for correcting and interpreting, this parallel phase migration error is automatically eliminated.

The convention referred to concerns the position on the ground ascribed to an integrated trace. We suppose that each integrated trace corresponds to the midpoint of the distance covered by the drops that we have integrated. Therefore, if the expression of the basic wave on trace No. 1 is

$$s_1 = A \sin 2\pi fT$$

then the expression of the trace which corresponds to a drop located at the assumed position of the integrated trace will be:

$$s' = A \sin 2\pi f(T - \Delta T/2) \quad \text{which is a maximum for}$$

$$2\pi f(T - \Delta T/2) = \pi/2 \quad \text{or}$$

$$T = \frac{1}{4f}(1 + 2y).$$

Comparing this value of T with the value previously obtained for the maximum of the integrated wave, we see that they are identically the same for any value of y; and, therefore, the parallel phase migration is always zero under the assumption described.

EXPERIMENTAL RESULTS

The preceding theory agrees perfectly with experiment, according to a group of test records which have recently been made in the laboratory of our company.

Four magnetic tapes were prepared: two of them representing a sequence of $2 \cdot 96 = 192$ weight drops with ideal signals impressed upon them and a phase difference of 23 milliseconds between drops No. 1 and No. 96, the phase increment remaining constant. Each tape contained 24 traces, each trace representing, therefore, 4 drops. The other two tapes were prepared in the same way with the only difference being that the phase difference between traces No. 1 and 96 was 125 milliseconds. In both cases, the frequency was 27 cps.

Based on these tapes, several composites were run. We have listed them below. The value of the phase coefficient y is obtained from the equation $y = 27 \cdot \Delta T$, where ΔT is the phase difference betwen the first and the last drop included in *one* integration (ΔT is either $.023 \cdot n/96$ or $.125 \cdot n/96$). The grading refers to the wave's shape; a good grade means that the wave is undistorted. The amplitudes remain unchanged because of A.V.C. action. A composite of a/b means that a consecutive traces are integrated and that there is an overlap of b traces between consecutive operations.

23 m.s. records:			
Composite	8/4	$y=0.052$	grade: good
Composite	24/20	$y=0.155$	grade: good
Composite	48/40	$y=0.311$	grade: good
Composite	80/76	$y=0.518$	grade: good
Composite	96/92	$y=0.621$	grade: good
125 m.s. records:			
Composite	8/4	$y=0.281$	grade: good
Composite	24/20	$y=0.841$	grade: poor
Composite	48/40	$y=1.69$	grade: cannot be used (badly distorted)
Composite	80/76	$y=2.81$	grade: cannot be used
Composite	96/92	$y=3.38$	grade: cannot be used

Notice the agreement between the values of y and the grades.

The author expresses his appreciation to the McCollum Exploration Co. for permission to publish this paper.

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BOUGUER CORRECTIONS WITH VARYING SURFACE DENSITY*

RAOUL VAJK†

ABSTRACT

The Bouguer correction is made, as a rule, to sea level and by using an average density value of the rocks, determined by the profile method. However, if the density of the rocks forming the topography varies from place to place, then the proper density value should be used for every topographical feature.

The Bouguer correction with varying density should be made only to a surface drawn through the low points of the topography. Below this surface, and to sea level, a constant density value should be used all over in the area; otherwise, nonexisting gravity anomalies may be introduced into the results of the survey, or existing gravity anomalies may be distorted.

A few examples are given for computing Bouguer corrections with varying surface density, and to illustrate the errors introduced by using improper density values.

INTRODUCTION

Topographical corrections of gravity data are made in order to eliminate the gravity effect of the topography and to transform all gravity data to the same level (sea level). These corrections are usually made in two steps. First, the gravity effect of the undulation of the topography in the vicinity of the gravity meter station is computed, which is called terrain effect; second, the gravity effect of a horizontal infinite sheet with a thickness equal to the elevation of the gravity meter station is determined, which is called Bouguer effect. The free-air correction due to the normal vertical gradient of the gravity is commonly combined with the Bouguer correction as both are linear functions of the elevation.

The terrain correction is usually small and in many cases it may be neglected. It follows that, in general, the Bouguer correction is the most important part of the topographical correction.

The topographical correction is a function of the density of the surface and near-surface rocks forming the topography, and of the density of all the rocks lying between the level of the lowest point of the topography and the sea level, as the Bouguer correction is made—as a rule—to sea level. In this paper the rocks above the level of the lowest point of the topography, within the area under investigation, will be referred to as surface rocks.

In order to compute the true Bouguer correction the density of the rocks above sea level should be known. The difficulties of density determinations are well known to geophysicists familiar with gravity surveys. At first (especially when the torsion balance was in use), densities of rock samples taken from the surface or near-surface of the earth were determined and these densities, or their

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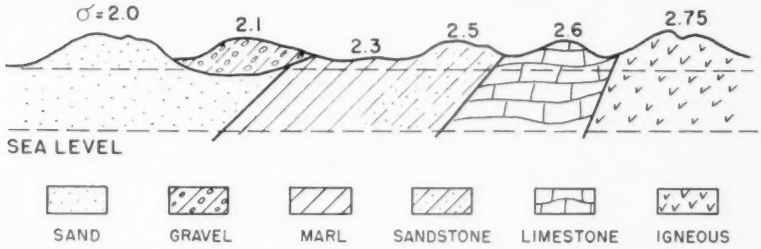

FIG. 1. Variations of surface density due to change of lithology.

average value, were used in computing the topographical effect. Later, average density values were used. When the gravity meter replaced the torsion balance, the profile method (Nettleton, 1939) was developed to determine the densities of the surface rocks.

THE CAUSES OF DENSITY VARIATIONS

The density values determined along various profiles in the same area usually show minor differences, mostly due to the inaccuracies of the density determination. It is customary to accept the average of all the determined values as true density. However, in certain areas the surface density may vary significantly within a relatively short area. This may be due to the different lithological character of the rocks forming various parts of the topography, as shown in Figure 1. The density may change considerably even within the same sand body if part of it is cemented to sandstone.

The normal distribution of density in sedimentary strata is an increase in density with the depth due mainly to compaction. If the topography is due to erosion of horizontal sedimentary strata, those parts of the topography which are built from the lower parts of the sedimentary section are generally of higher density, while those consisting of the upper part of the section have relatively lower densities (Figure 2). A hundred-meter elevation difference in shale may cause a change of 0.1 g/cm^3 in the density value. In this case higher elevations are associated with lower surface densities and vice versa.

There may be areas where faulting is the main factor in forming the topographical relief (Figure 3). In such areas the higher blocks have higher average

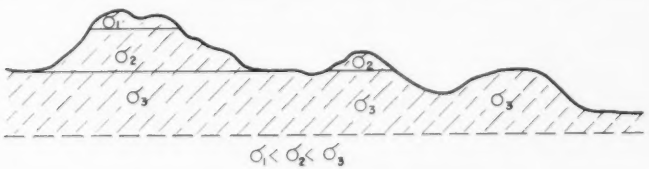

FIG. 2. Variation of surface density due to erosion.

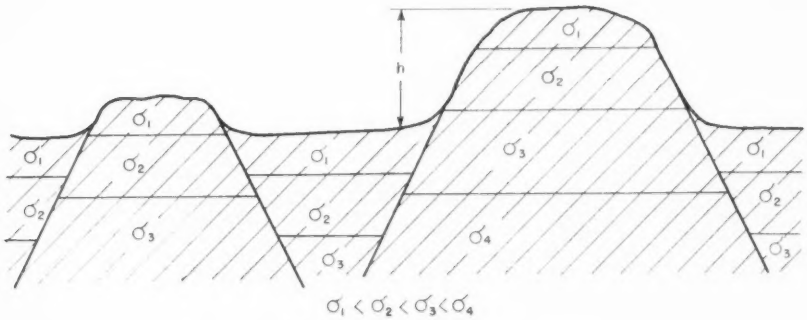

FIG. 3. Variation of surface density due to faulting.

densities than the lower ones. That is, higher densities are related to higher elevations. The same is true if the topography is formed by moderately eroded folds (Figure 4). However, if the erosion cuts the same fold into individual topographical highs of about the same relative elevation, they may have different density values, as is illustrated in Figure 5. A combination of faulting, folding, erosion and lithological changes may complicate the density distribution in the surface rocks infinitely.

These latter examples (Figures 4 and 5) have, of course, mostly theoretical

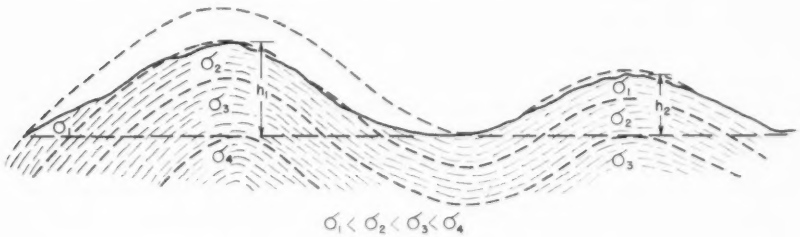

FIG. 4. Variation of surface density due to folding and erosion.

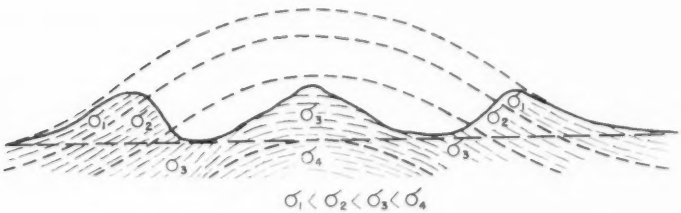

FIG. 5. Variation of surface density due to the erosion of an anticline.

interest only: geophysical work is usually not required in such cases. However, the gravity survey sometimes is made before the geological (or simultaneously).

In a detailed study of surface densities determined by the profile method, it was found that the density of the surface rocks in that particular area varies actually at least between 2.2 and 2.5. By determining the density values of the surface rocks at every station where suitable topographical relief exists, and by interpolating missing values, sufficient data may be obtained to outline the areas with the same surface density; and thus a density contour map may be constructed.

THE USE OF AVERAGE OR VARYING DENSITY

After the density contours are drawn, the following questions may be raised:

1. Should the topographical corrections be made with varying density, or with the average density?

If the answer to the first part of this question is yes:

2. How to compute topographical corrections for varying density?

Some consideration is necessary before the first question is answered. The aim of the topographical corrections is to relieve the gravity data from the effect of the undulating topography. This can be done only if proper density data are applied. The profile method was developed to determine the true surface density in a particular area as it may change considerably in different parts of a region. It is only going one step further to realize that the surface density may change even within the same area. If it is necessary to use the proper density value for each area, it seems logical to use the proper density value for each part of the area.

However, it should be borne in mind that a detailed study of the density requires gravity stations located along long straight traverses in various parts of the area, and a considerable amount of computation. Such a study is time consuming and expensive. Furthermore, if the topographical relief is small, 10–20 meters, the change of the Bouguer correction corresponding to a density variation of 0.1–0.2 g/cm^3 is negligible. (See Table.) With 100 meter elevation, a density change of 0.1 g/cm^3 alters the Bouguer correction by 0.4 milligals. (Elevations considered here are relative elevations; that is, above the lowest point of the topography.) Therefore, the knowledge of an approximate average density is sufficient in most cases for computing the Bouguer corrections in a low relief area (relative elevations below 50 meters) though the importance of obtaining accurate density values increases with increasing relative elevations or when investigating very small gravity anomalies. Naturally, if important density changes occur in the area, errors of several tenths of a milligal may be made by using the average density instead of the true density values even in areas with moderate topography. From these it is obvious that the accuracy of the survey is improved by using accurate local density data for topographic corrections in areas with considerable relative elevations and/or with considerable density changes.

Still another objection may be raised. Namely, the profile method gives the

BOUGUER CORRECTIONS IN 1/10 OF A MILLIGAL UNIT
$\Delta g = 0.419\sigma H_m \ 10^{-4}$ gal.

σ, Density	Elevation, H_m							
	5 m	10 m	20 m	30 m	40 m	50 m	100 m	200 m
0.05	1.10	0.21	0.42	0.63	0.84	1.05	2.10	4.19
0.10	0.21	0.42	0.84	1.26	1.68	2.10	4.19	8.38
0.15	0.32	0.63	1.26	1.89	2.51	3.14	6.28	12.57
0.20	0.42	0.84	1.68	2.51	3.35	4.19	8.38	16.76
0.25	0.52	1.05	2.10	3.15	4.19	5.24	10.48	20.95
0.30	0.63	1.26	2.51	3.77	5.03	6.28	12.57	25.14
0.40	0.84	1.68	3.35	5.03	6.70	8.38	16.76	33.52
0.50	1.05	2.10	4.19	6.29	8.38	10.48	20.95	41.19
1.00	2.10	4.19	8.38	12.57	16.76	20.95	41.90	83.80

density of the rocks forming the topographical relief, but it cannot give any information as to the density of the rocks below the level of the lowest point of the topography. The density distribution below this level may be quite different from that above it (see Figure 6). In this case the gravity anomalies due to near-surface density changes for which no correction can be made, may be of the same order as the change of the Bouguer corrections due to the density variations of the surface rocks. For this reason the reliability of the computed gravity anomalies will not be improved by an elaborate surface density determination. In such cases it may not be worth-while to use a variable density, and it is probably wiser to regard as unreliable all the small gravity anomalies with intensity comparable to the gravity effects due to density changes in the surface, or near-surface rocks. Still, the knowledge of the density variations of the surface rocks may be useful in determining the critical amplitude for the reliable and unreliable gravity indications.

In all other cases discussed above (Figures 2–5) the application of the proper density values in the Bouguer corrections will improve the gravity data.

It should be realized that the effect of the topography cannot always be

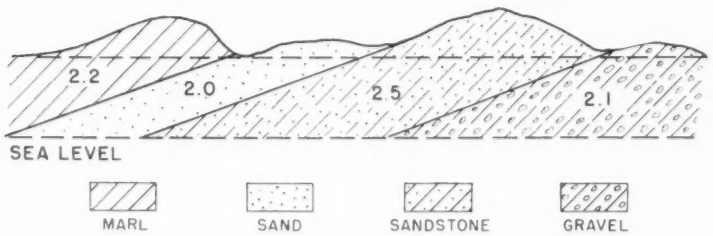

FIG. 6. Variation of density below the datum level of the topography

readily recognized in the gravity anomalies. This is especially true if the anomaly and the error in the topographical correction are of about the same intensity, same extension and they partly overlap. The anomaly shown in Figure 7a, does not seem to be correlated to the topography (Figure 7b) although in fact its intensity, location and extension are affected by an error made in the topographical correction because of using a too small density value in the Bouguer correction (Fig. 7c). The true anomaly is shown in Figure 7d.

There is another case when application of different densities in the topographical corrections is necessary; namely, when two gravity surveys made independently in neighboring areas connect and it is desirable to unite the two maps, which were corrected for different densities into a single one. Applying the

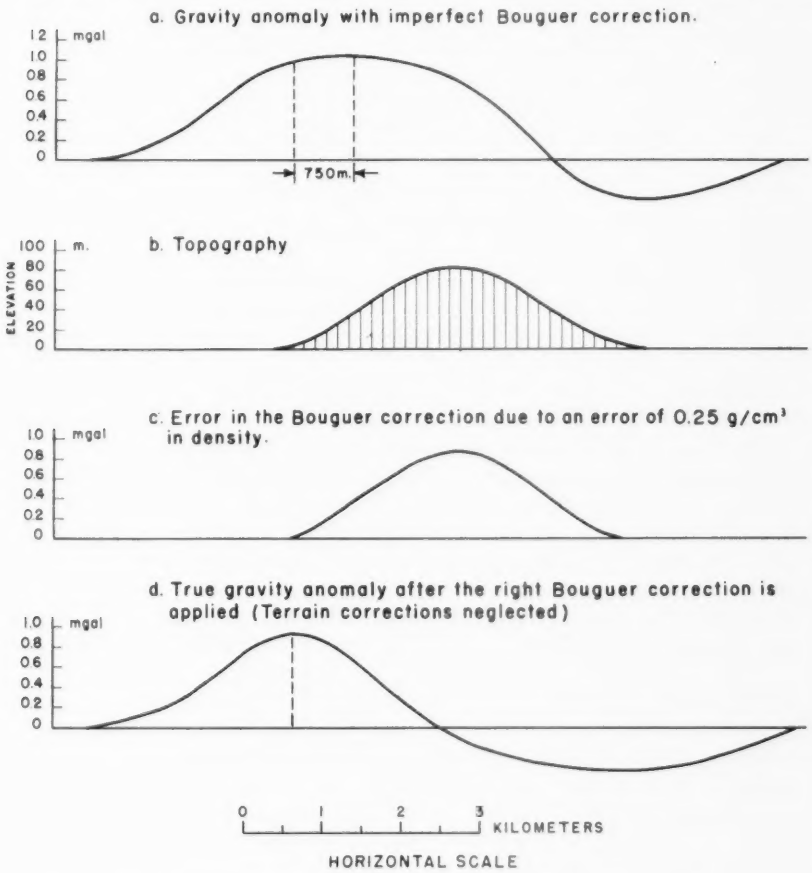

FIG. 7. Distortion of a gravity anomaly by imperfect Bouguer correction.

density value determined as best in one area, for computing the topographical corrections in the other area, would introduce errors in the anomalies observed in the latter, and vice versa.

From the above discussion, it may be concluded, as an answer to the first question, that there are cases when an application of the varying density values, instead of an average density, is desirable when computing the Bouguer corrections.

COMPUTATION OF THE TOPOGRAPHICAL CORRECTIONS FOR VARYING DENSITY

The second question was: How to compute topographical corrections for varying density? Applying variable density for Bouguer corrections to the sea level would in most cases introduce considerable errors into the gravity anomalies, distorting the actual anomalies. In the following, a method is given to compute Bouguer corrections with variable surface densities, without introducing appreciable errors into the observed anomalies.

Before further discussing this problem, the profile method to determine the density of the surface rocks and the meaning of the Bouguer correction should be reviewed.

REVIEW OF THE PROFILE METHOD

The profile method adopted generally for determining densities of surface rocks can be used only if:

1. The gravity anomalies are smooth compared to the topographic relief.
2. Topography is not correlated with subsurface structure.
3. The gravity stations along the profile are located on a straight line or on a smooth curve.
4. A smooth regional topographical surface can be drawn along the profile on which the local topographical highs are superimposed or there are definite "breaks" in the smooth curve representing the topography.

The fourth condition listed may need some explanation. The regional topographical surface may be a horizontal plane, as in Figure 8a; or a tilted plane, as in Figure 8b; or finally any other smooth surface, as in Figure 8c. In all cases the density determined by the profile method may be attributed only to the rocks above these datum surfaces. The profile method gives no information about the density of rocks below these datum surfaces. Therefore, any variations of density below these surfaces can be obtained only from other sources (geological data, well logs, etc.).

As pointed out by Nettleton (1939), the density value obtained by the profile method gives, instead of the true density, an apparent density which corrects for both the anomalous vertical gradient and a possible erroneous instrument constant.

Disregarding errors, it is easy to prove that, in case of a horizontal datum plane, the density value obtained by the profile method is a weighted average of the densities of the rocks forming the topography.

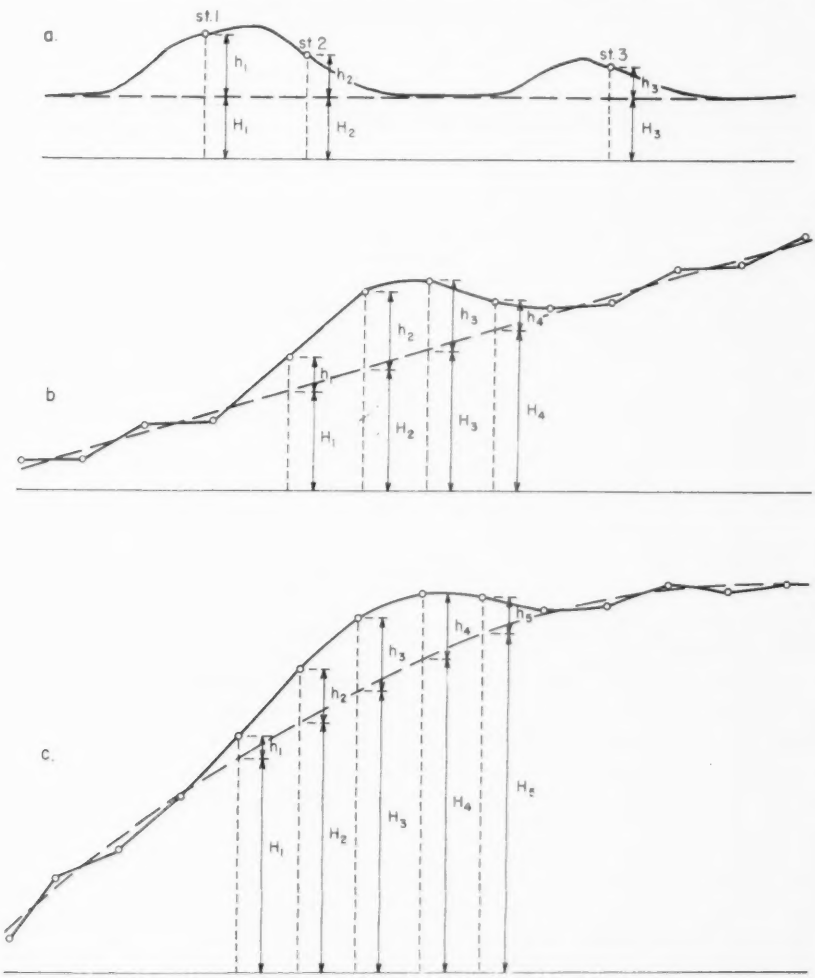

FIG. 8. Separation of local topography from regional topography.

Namely, the gravity effect due to the masses forming the topography is at Station A. (See Figure 9a.)

$$\Delta g = f \int_V (dv\sigma/r^2) \cos \phi = f\sigma' \int_V (dv/r^2) \cos \phi, \qquad (1)$$

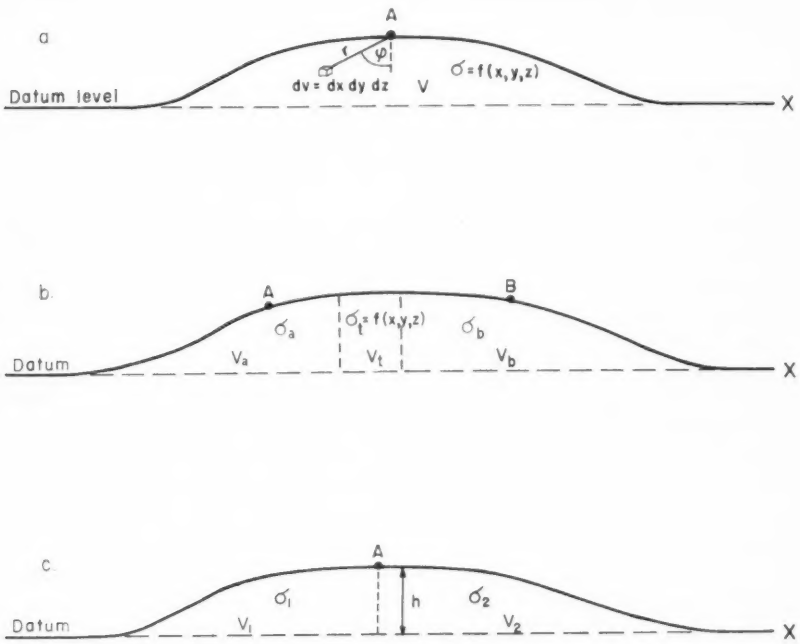

FIG. 9. Density distribution in a topographical feature.

that is

$$\sigma' = \frac{\int_V (dv\sigma/r^2) \cos \phi}{\int_V (dv/r^2) \cos \phi}, \tag{2}$$

or, if the terrain effect is negligible,

$$\sigma' = \frac{\int_V (dv\sigma/r^2) \cos \phi}{2\pi h}. \tag{3}$$

The same is true if the density of the rocks in the vicinity of Station A is σ_a = constant, in the vicinity of Station B is σ_b = constant, and in a transitional zone V_t between Stations A and B σ_t varies between the limits σ_a and σ_b. (See Figure 9b). Then:

$$\sigma' = \frac{\sigma_a \int_{V_a} (dv/r^2) \cos\phi + \int_{V_t} (dv\sigma_t/r^2) \cos\phi + \int_{V_b} (dv/r^2) \cos\phi}{\int_V (dv/r^2) \cos\phi}, \quad (4)$$

where $V = V_a + V_t + V_b$.

This analysis proves that we do not have to be concerned about how the density changes between two stations, whether the change is abrupt (along a vertical plane, or other surface), or the change is transitional. This is taken care of in the weighted average density value determined by the profile method.

Naturally, the weighted average density σ' is a function of the location of the gravity station and a different apparent density value will be obtained for every station.

If the gravity Station A is exactly at the density contact (as shown in Figure 9c), and assuming that the terrain correction is negligible, then $V_1 = V_2 = V/2$

$$\sigma' = \frac{\sigma_1 \int_{V_1} (dv/r^2) \cos\phi + \sigma_2 \int_{V_2} (dv/r^2) \cos\phi}{\int_V (dv/r^2) \cos\phi} = \frac{\sigma_1 + \sigma_2}{2}. \quad (5)$$

For stations left of A, density values between σ_1 and $(\sigma_1+\sigma_2)/2$ will be obtained, and for stations right of A, density values between $(\sigma_1+\sigma_2)/2$ and σ_2. If the horizontal distance from Station A is great, as compared to the elevation h measured from the datum level, then the density approaches σ_1 or σ_2, respectively.

The same result will be obtained in the above described cases if, when needed, a terrain correction is applied. An approximate density value is usually satisfactory for making the terrain corrections.

REVIEW OF THE BOUGUER CORRECTION

In connection with the Bouguer correction, the writer wishes to emphasize the following points.

The Bouguer formula gives the gravity effect of an infinite horizontal sheet of material with a constant density. However, actually (1) the topography is never an infinite horizontal sheet, and (2) its density often varies in both vertical and horizontal directions. In spite of these facts the Bouguer formula is generally used in correcting gravity data for topography, as the deviations from primary assumptions do not result in serious errors in most cases. Furthermore, as will be shown below, these errors may be compensated in the density value determined by the profile method.

It should be remembered that the aim of the Bouguer correction in prospecting surveys is, first of all, to eliminate the gravity effects of the topography. In

order to eliminate the effects of the topography, a Bouguer correction to the level of the lowest point of the topography is sufficient and it is not necessary to make corrections to sea level.

DATUM LEVEL FOR TOPOGRAPHICAL CORRECTIONS

The level to which the Bouguer and free-air corrections are calculated will be called datum level. This may be the level of the lowest point of the topography within that particular area, or in a part of the area (local datum level); it may be sea level, or any other level or surface chosen for convenience.

Applying the Bouguer and free-air corrections does not mean that the gravity anomaly at a lower level (datum level) below the station is obtained. Actually only the gravity effect of the masses between the station and the datum level is removed and the change of gravity due to the normal vertical gradient is subtracted. The gravity effects of mass deficiencies or mass surpluses, due to density changes in horizontal direction occurring above the datum level (up to the surface), will remain in the gravity values corrected for a constant density, and no correction is made for the local anomaly of the vertical gradient.

The errors caused by using incorrect density values, and the effect of using varying density in the Bouguer corrections made to sea level instead of the datum level, are shown in Figure 10. If the density distribution is as in Figure 10a, and the Bouguer correction is made with σ_1, then the gravity effect of a mass shown in Figure 10b (horizontally hatched area) with a density $\sigma_2-\sigma_1$ will remain in the corrected gravity values. Similarly if σ_2 is used, the gravity effect of a mass deficiency corresponding to the density difference $\sigma_1-\sigma_2$ (Figure 10c) will appear. That is, in the first case the gravity effect of the topography on the right side of A is insufficiently compensated, while in the second case the gravity effect of the topography left of A is overcompensated by the Bouguer corrections. Similarly, the result is erroneous (insufficient compensation on the right side and overcompensation on the left side of A) if the Bouguer corrections are made with the average density $\sigma_{av}=(\sigma_1+\sigma_2)/2$ (Figure 10d). In Figure 10e, σ_1 was used in the Bouguer corrections over the left side and σ_2 over the right side of the topography, resulting in a correct topographical correction. In the above examples, the Bouguer correction was made to the datum level of the topography. Using the same density values (σ_1, σ_2 and σ_{av}), but applying the Bouguer corrections to sea level instead of to the local datum in Figures 10f, 10g, and 10h, the same results were obtained as in Figures 10b, 10c, and 10d (disregarding, of course, an additional constant). This is because the relative gravity values remain the same, regardless of the datum level of the Bouguer correction, if a constant density is used all over the area.

Using σ_1 in the left side of the area and σ_2 in the right side (as in Figure 10e), but making the Bouguer corrections to the sea level instead of the datum level of the topography, a gravity anomaly corresponding to a fault at A will appear

(Figure 10i) which is, of course, erroneous. Densities of the surface rocks must not be attributed to rocks below the datum level of the topography; in so doing, we may introduce false gravity anomalies into the gravity data.

It is possible, of course, that the change of the density of the surface rocks at A is due to a fault, as shown in Figure 10a′. If the same Bouguer corrections are used in Figures 10b′, c′, d′ and f′, g′, h′ as were used in Figures 10b, c, d and f, g, h, respectively, then the corresponding results will be the same (in Figure 10b′ the same as in Figure 10b, in Figure 10c′ the same as in Figure 10c, and so on) except that a gravity effect of a fault at A is added to the gravity effects in Figures 10a, b, c, etc.

Applying σ_1 and σ_2 densities in the Bouguer corrections made to the local datum level on the left and right side of the fault, respectively, the gravity effect of that part of the fault which is above the datum level of the topography is removed from the gravity values (Figure 10e). If the Bouguer corrections with the same densities are made to the sea level, the gravity effect of that part of the fault which is above sea level is eliminated from the gravity values (Figure 10i). This is another reason why Bouguer corrections with varying densities should be made only to the datum level of the topography and not to sea level. It is emphasized that, using variable densities for the Bouguer corrections, only gravity effects of geological structures *below* the datum level are indicated in the corrected gravity anomalies. But this is actually what the aim of the topographical corrections should be, i.e. to remove all gravity effects originating within the topographical relief. When an average density, or any constant density, is used in the Bouguer corrections, the gravity effect of the entire geological structure, up to the top of the topography, will remain in the gravity data.

In many cases, as discussed in the review of the profile method, it is not possible to determine the densities of all the rocks above the level of the lowest point of the topography, but only of the rocks above certain datum surfaces (see Figures 8a, b and c). In these cases, of course, the gravity effect of geological structures below these datum surfaces will remain in the gravity data.

Although, as stated above, for prospecting purposes, it is sufficient to make the Bouguer correction to the level of the lowest point of the topography, it is customary to correct all gravity data to sea level. This makes it possible to tie the individual gravity meter surveys to pendulum stations. It makes the values of the gravity anomalies in various surveys comparable. The Bouguer corrections for the masses below the lowest point of the topography should be made with a constant density value all over the area. The writer believes that if there are any gravity anomalies due to the change of density in horizontal direction between the level of the lowest point of the topography and the sea level, they may be correctly called subsurface anomalies and these anomalies should not be subject to change by the Bouguer corrections; to eliminate or disregard them is the task of the interpreter.

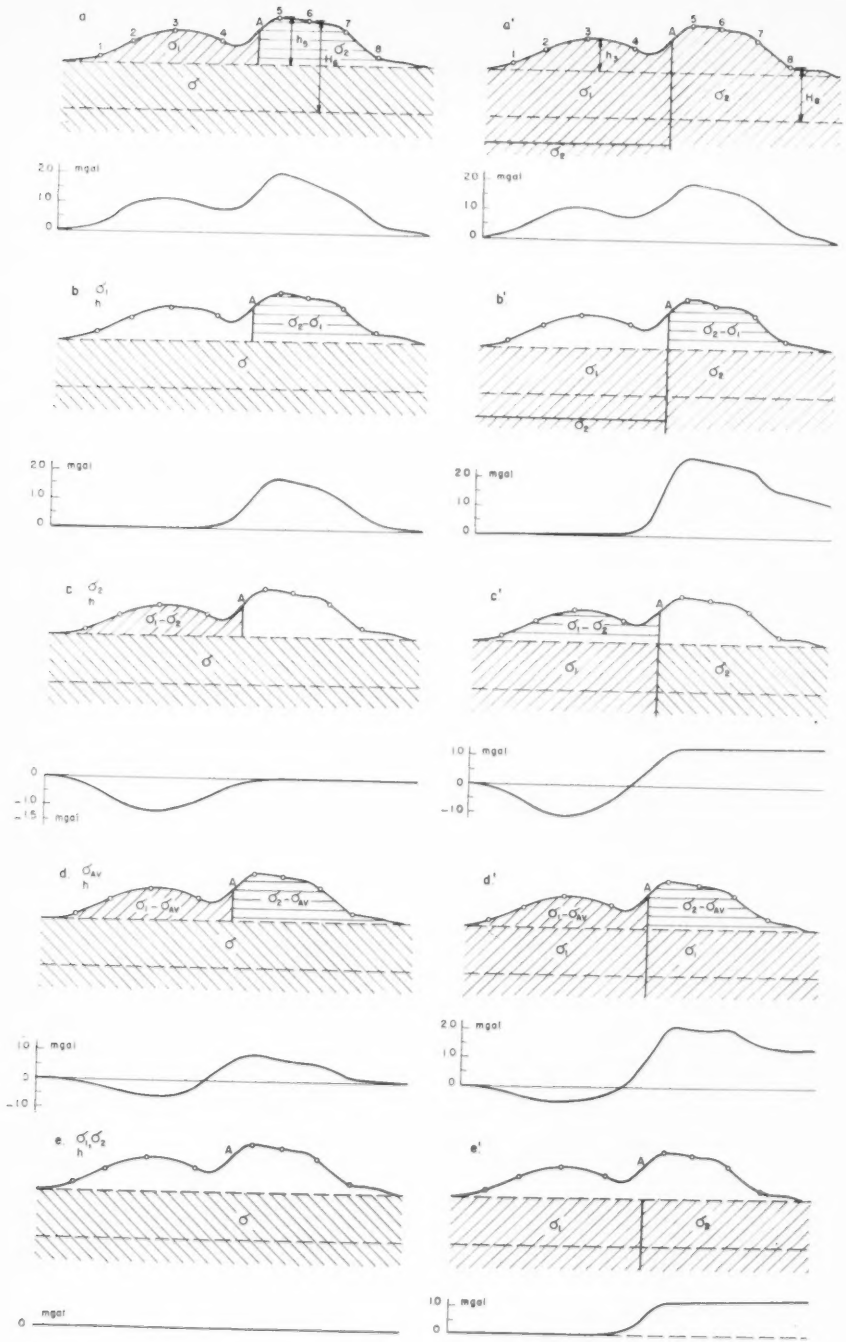

FIG. 10. Errors caused by using improper density values in topographical correction.

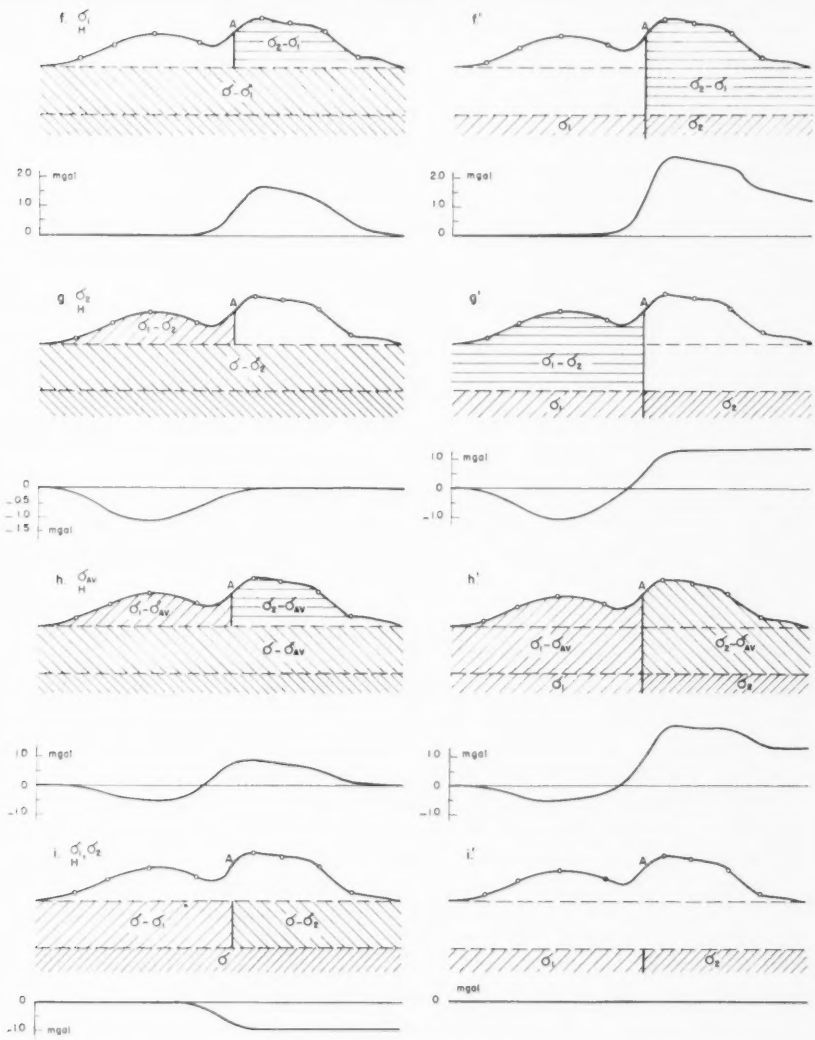

FIG. 10. Errors caused by using improper density values in topographical correction.

SUMMARY

Summarizing the results of the various Bouguer corrections presented in Figure 10, it may be stated:

1. If the density of the surface rocks varies, the effect of the topography cannot be eliminated from the gravity data by computing the Bouguer correction with any constant density.
2. Bouguer corrections with varying density must be used only to the datum surface of the topography (as determined in Figure 8); otherwise erroneous anomalies may be introduced into the gravity data, or part of the true anomalies may be removed.
3. Bouguer corrections from the datum surface of the topography to sea level should be made with a constant density over the entire area.

If there is geological information as to the character and thickness of rock strata between the lowest point of the topography and the sea level, and density values may be assumed to these strata, the Bouguer corrections may be adjusted accordingly, as suggested by Nettleton (1939). However, the writer believes that such adjustments should not be included in the routine topographical correction and that this task should be reserved for the interpreter.

The above summary, especially the items under 2 and 3, is the answer to our second question: How to compute the topographical corrections for varying density?

Following this method, that is, using the varying density only for corrections to the local datum surface, all the gravity effects caused by the topographical relief and by horizontal density changes due to lithological and geological reasons, *above the local datum* surface, are removed from the gravity data. The writer believes that attributing the varying density data to a minimum thickness of surface rocks (above the datum surface) greatly reduces the hazard of making serious errors, and this method should result in a better Bouguer anomaly map (less related to topography) than when an average density is used.

Applying the profile method in a large area with considerable and complicated topographical relief, it may be found that, by using the level of the lowest point of the topography for datum level, the relative elevations will be still too large to assume that the local surface densities are valid throughout the entire column above this datum plane. (See Figure 11.) In such cases different density values may be obtained and should be used for the secondary topographical relief (relative elevations h_1, $h_2 \cdots$) and for the primary topographical highs (relative elevations h_1', $h_2' \cdots$). A constant density should be used for the Bouguer corrections corresponding to elevations $H_1 \cdots H_n$.

In Figure 11 the actual gravity anomaly is shown and also the erroneous anomaly obtained by using the average density of 2.15 instead of the proper densities for each topographical feature. This example shows also the usefulness of computing the Bouguer correction for variable density instead of a constant (average) density if a high accuracy of the survey is requested.

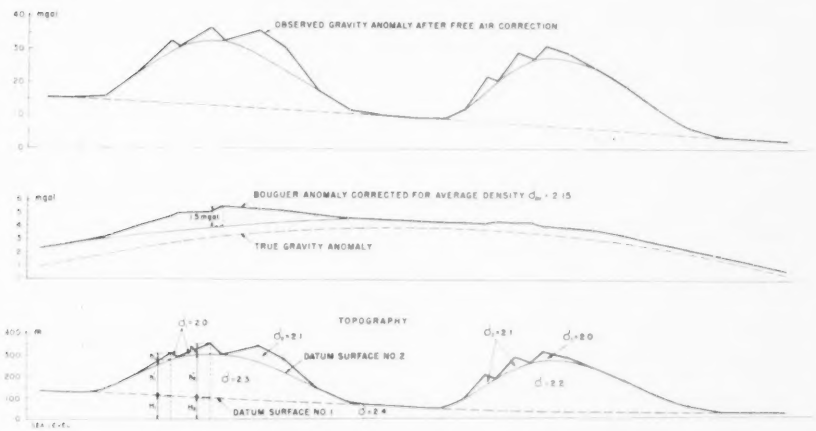

FIG. 11. Errors caused by using average density values in topographical correction.

After the above discussions there is no problem to connect two gravity surveys corrected for different densities. Suppose density σ_1 was used in one area, σ_2 in the other area and $\sigma_1 > \sigma_2$. In that case, the gravity values corrected for the larger density σ_1 should be accepted while the gravity values of the other area should be recalculated. The new gravity values for the second area can be obtained by calculating the Bouguer corrections with σ_2 only to the local datum surface and using σ_1 for Bouguer corrections from the local datum surface to the sea level. (See Figure 12.)

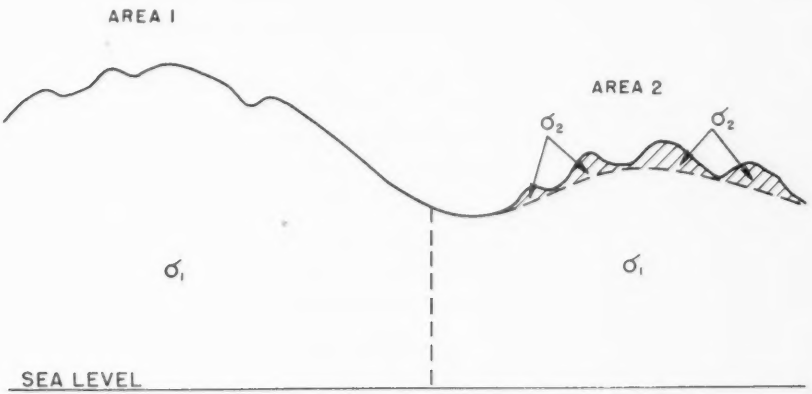

FIG. 12. Proper densities to be used in the Bouguer correction.

The isogams drawn on these new gravity values in the second area will connect without difficulty the isogams of the first area. For satisfactory results, it is necessary, of course, that σ_1 and σ_2 were determined correctly by the profile method.

ACKNOWLEDGMENT

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REFERENCE

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GEOPHYSICS, VOL. XXI, NO. 4 (OCTOBER, 1956), PP. 1021-1040, 11 FIGS.

ELEMENTARY APPROXIMATIONS IN AEROMAGNETIC INTERPRETATION*

D. W. SMELLIE†

ABSTRACT

Total magnetic intensity anomaly expressions are derived for four simple sources: the point pole, line of poles, point dipole and line of dipoles. Type curves are presented for the point pole and dipole. For all cases, factors are calculated which may be multiplied into the half-maximum distances on the anomaly profiles to yield depth estimates. These methods serve as a first approximation in the interpretation of aeromagnetic data, but their limitations must be kept in mind. Two examples of the application of the methods are given.

INTRODUCTION

Although "flux-gate" type total magnetic intensity instruments have been used for aeromagnetic prospecting for some ten years, only a small amount of material has appeared in the literature pertaining to the interpretation of data. Henderson and Zietz (1948) have calculated factors for depth determinations using the point pole and line of poles approximations. This work is modified in the present paper. Vacquier et al. (1951) have used vertical prismatic models for interpreting deep anomalies. Various procedures have been developed for treating the data, such as the computation of second vertical derivatives (Henderson and Zietz, 1949a), the upward continuation of anomalies (Henderson and Zeitz, 1949b) and the computation of vertical magnetic anomalies from total magnetic field measurements (Hughes and Pondrom, 1947). Peters (1949) has described analytical methods for interpreting vertical magnetic intensity data in deep basement areas which may readily be extended to the total magnetic field case. All these methods depend on the anomalous field being small compared with the normal total intensity of the earth's field, in which case the anomalous field is a harmonic function.

In this paper, four approximate methods are presented—the point pole, line of poles, point dipole and line of dipoles. Type profiles of total magnetic intensity are given for the point sources. For all four type sources the peak displacement is calculated, and factors for depth determinations using the two distances from maximum to half-maximum along the anomaly profile.

GENERAL CONSIDERATIONS

Potential fields of any type are inherently ambiguous. In other words, theoretically an infinite number of solutions may be obtained for the physical

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property distribution giving rise to a particular anomaly, be it magnetic, gravitational or electrical. Of course, only a limited number would be likely on geological grounds. The present simple models indicate depths to the equivalent pole or dipole of the source.

In aeromagnetic surveying, two general classes of problems present themselves. There are the surveys of sedimentary basins where the strongest anomalies are due to lithologic contrasts within the basement. If sufficient susceptibility contrast exists between the sediments and basement complex, this is reflected in a broad profile which reflects the basement structure. Basement highs then yield local anomalies but unambiguous interpretation of these is difficult. The simple models may be useful as a first approximation for depth estimates, but the prism models of Vacquier et al. (1951) can often give more enlightening results. Surveys of this type are usually flown at constant elevation above sea level and are mainly of interest to the petroleum industry.

The shallow-source problem on the other hand, of interest in mining geophysics, deals with magnetic bodies close to the earth's surface and hence surveys are generally conducted at a fixed average height above terrain, usually five hundred feet. Rugged terrain can introduce complexities in the profiles, but in country of low topographic relief the results are amenable to analysis. All four approximations have been useful, as well as the two-dimensional dike and vertical contact problems. Anomalies which duplicate the theoretical model curves are rare, with the result that the models are used only as a guide to qualitative interpretation.

Figure 1 shows the total intensity anomaly on a *meridional* profile passing directly over the point source, in both the northern and southern hemispheres. These illustrate the features of the normal type of profile encountered in practice and the *correspondence between hemispheres*.

The applicability of the approximations depends on the geomagnetic latitude and the dimensions of the source. When the width of the body is small compared to its depth and it is elongated in the direction of polarization, the pole approximations yield the depth to the top. Thus, narrow vertical dikes would yield to a line of poles approximation at high geomagnetic latitudes. However, in low geomagnetic latitudes the dipole moment would make a larger contribution to the observed field. For bodies of limited extent in depth, the dipole approximations yield the depth to the center, the point dipole for bodies approaching a sphere in shape, the line of dipoles a horizontal cylinder. Sources which are wide compared with their depth will give broad profiles and depth determinations made from them give values that are too large. This is also the case with complex sources consisting of several closely spaced anomalous bodies whose effects merge to give a single anomaly. The estimated depth will be a maximum value, useful at least for distinguishing shallow from deep-seated sources.

Interpretation of anomalies characterized by nearly circular contours may be approached using a pole or dipole method, while those with contours elongated

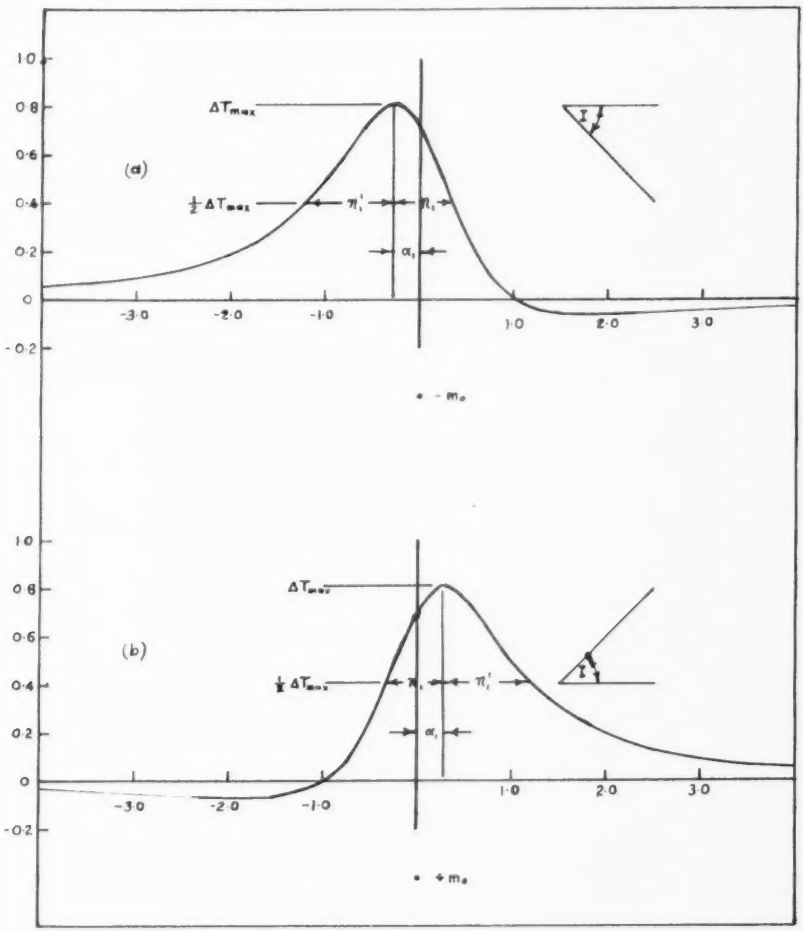

FIG. 1. Total intensity anomaly due to point source in (a) northern and (b) southern magnetic hemispheres, showing profile in units of depth at geomagnetic latitude 45°. The anomalous field component ΔT is expressed in units of m_0/ζ^2.

in one direction require a line of poles or line of dipoles. The choice between pole and dipole approximations is best made by considering the intensity of the minimum in relation to the maximum (Figures 3, 7). Finally, it must be emphasized that the methods serve as a guide to geological reasoning and more elaborate theoretical methods.

POINT POLE APPROXIMATION

Theory for the total intensity anomaly due to a point pole in the northern hemisphere has been presented (Henderson and Zietz, 1948), but is modified in the present work. In the northern magnetic hemisphere, a narrow body greatly extended in depth whose long axis is close to the direction of polarization, if polarized normally may be represented by a negative magnetic pole at its upper end.

Using an orthogonal Cartesian co-ordinate system, z-axis vertically downward, pole $-m_0$ at $z=\zeta$, the anomalous magnetic potential ΔV is given by

$$\Delta V = -\frac{m_0}{[x^2 + y^2 + (z - \zeta)^2]^{1/2}}. \tag{1}$$

In the xy-plane, the total intensity anomaly $\Delta T(x, y, 0)$ is

$$\Delta T(x, y, 0) = -m_0 \frac{x \cos I \cos \beta + y \cos I \sin \beta - \zeta \sin I}{[x^2 + y^2 + \zeta^2]^{3/2}}, \tag{2}$$

where the x-axis makes an angle β with magnetic north and the y-axis is in the northerly half-plane. I is the inclination of the total field T. A profile along the y-axis is given by

$$\Delta T(y) = m_0 \sin I \frac{\zeta - ay}{[y^2 + \zeta^2]^{3/2}} \tag{3}$$

where $a = \cot I \sin \beta$. (4)

The peak value ΔT_{max} occurs when $\beta = 90°$ at the point

$$y = -\zeta\alpha_1$$

where

$$\alpha_1 = [(9 + 8 \cot^2 I)^{1/2} - 3]/4 \cot I, \tag{5}$$

and its value is

$$\Delta T_{max} = m_0 \sin I(1 + \alpha_1 \cot I)/\zeta^2(a_1^2 + 1)^{3/2}. \tag{6}$$

The minimum value occurs at

$$y = \zeta\gamma_1,$$

where

$$\gamma_1 = [3 + (9 + 8 \cot^2 I)^{1/2}]/4 \cot I \tag{7}$$

and its value is

$$\Delta T_{min} = m_0 \sin I(1 - \gamma_1 \cot I)/\zeta^2(\gamma_1^2 + 1)^{3/2}. \tag{8}$$

Also,

$$\Delta T(y) = 0, \qquad \text{when} \qquad y = \zeta \tan I. \tag{9}$$

We wish to calculate factors which, when multiplied into the distance from maximum to half-maximum intensity along a meridional profile, yield the depth to the point pole. We transform our origin to the peak of the anomaly, taking the y-axis along the magnetic meridian, obtaining

$$\Delta T(y') = m_0 \sin I \frac{\zeta(1 + \alpha_1 \cot I) - y' \cot I}{[y'^2 - 2\alpha_1 \zeta y' + \zeta^2(1 + \alpha_1^2)]^{3/2}}. \tag{10}$$

Substituting $y' = \zeta/k$ in equation (10) and equating with $\frac{1}{2}\Delta T_{\max}$ from equation (6), we obtain

$$\frac{1 + \alpha_1 \cot I}{2(\alpha_1^2 + 1)^{3/2} k^2} = \frac{k(1 + \alpha_1 \cot I) - \cot I}{1 - 2\alpha_1 k + k^2(1 + \alpha_1^2)^{3/2}}. \tag{11}$$

This may be solved numerically for two real roots, a positive $k_1(a)$ and a negative $-k_1'(a)$. They are to be used when η, the distance from the anomaly maximum to half-maximum in a northerly direction, and η' in a southerly (in the northern hemisphere). These directions are reversed in the southern hemisphere, cf. Figure 1.

The depth $\zeta = k_1\eta = k_1'\eta'$. The ratio of half-maximum distances $\eta : \eta'$ on the actual anomaly should approximate the theoretical ratio $\eta_1 : \eta_1' = k_1' : k_1$ if the point pole is an adequate representation of the physical situation. The peak displacement α_1, the factors $k_1(a)$, $k_1'(a)$ and the ratio $\eta_1 : \eta_1'$ are given in Figure 2. A family of ΔT profiles corresponding to various values of I is presented in Figure 3. Similar notation is used in the subsequent three cases, subscripts 2, 3, 4, corresponding to line of poles, dipole and line of dipoles respectively.

Since a contour aeromagnetic map is normally made up in practice, it was thought sufficient to determine the $k-$ factors for the case $\beta = 90°$ corresponding to profiles taken through the anomaly maximum, along the magnetic meridian. In a given practical case, the distances η_1 and η_1' are measured on a meridian profile. These may be multiplied by the factors $k_1(a)$ and $k_1'(a)$ respectively to yield two depth determinations. If the maximum is difficult to locate, we may measure the distance η'' between points of half-maximum intensity and determine $\zeta = k_1''\eta''$ where

$$k_1''(a) = \frac{k_1(a)k_1'(a)}{k_1(a) + k_1'(a)}. \tag{12}$$

A transverse ($\beta = 180°$) profile through the maximum may serve as a check. This is symmetrical. The width between points of half-maximum intensity η_τ'' per unit depth is given by

$$\eta_\tau'' = 1.533(1 + \alpha_1^2)^{1/2}, \tag{13}$$

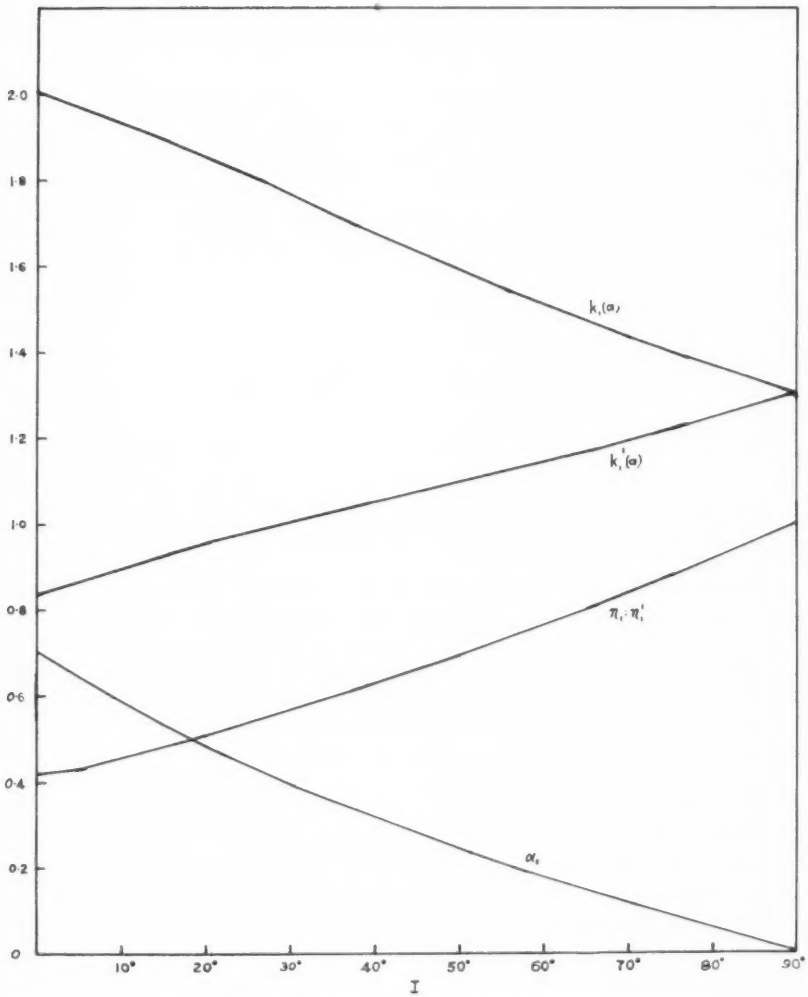

FIG. 2. Total intensity depth factors $k_1(a)$ and $k_1'(a)$, half-maximum distance ratio $\eta_1:\eta_1'$ and peak displacement α_1 for point source.

and therefore the depth factor k_r'' is given by

$$k_r'' = 0.652(1 + \alpha_1^2)^{-1/2}. \qquad (14)$$

The work of Henderson and Zietz (1948) should be referred to. These authors

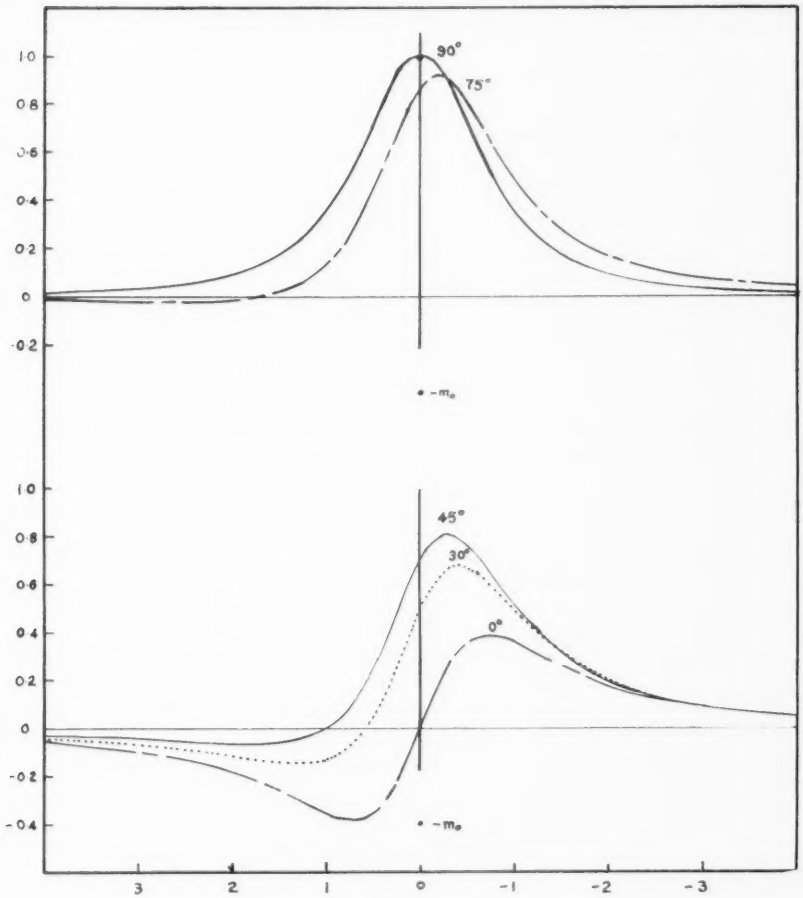

FIG. 3. Total intensity anomaly from a point source at various geomagnetic latitudes (northern hemisphere). Profiles in units of depth along magnetic meridian. The anomalous field component ΔT is in units of m_0/ζ^2.

find the maximum anomaly and one half-maximum point on lines in any direction passing directly above the point pole. Of these lines, only that in the magnetic meridian passes through the absolute anomaly maximum, giving the results presented above. For all other directions the absolute maximum lies to the south of the line (in the northern hemisphere).

In the southern magnetic hemisphere, our type body would be represented

by a positive magnetic pole. The magnetic potential is now

$$\Delta V = \frac{m_0}{[x^2 + y^2 + (z - \zeta)^2]^{1/2}} \tag{15}$$

and for a profile along the meridian (y-axis.),

$$\Delta T(y) = m_0 \sin I \frac{\zeta + ay}{(y^2 + \zeta^2)^{3/2}} . \tag{16}$$

This expression is merely a mirror image of that for the northern hemisphere. As a result, we may use our northern hemisphere results in the southern hemisphere, provided that we take our distances from maximum to half-maximum η in a southerly direction and η' in a northerly direction.

LINE OF POLES

The theory for this approximation is also given by Henderson and Zietz (1948), who give factors

$$k_2(a) = \frac{a}{2b}\left[1 + \left(\frac{3b - 1}{b - 1}\right)^{1/2}\right], \tag{17}$$

where

$$b = (a^2 + 1)^{1/2}, \tag{18}$$

as a function of inclination of the total field I and angle β between strike of body and magnetic north. These factors are for depth determinations using profiles perpendicular to the strike of the anomaly. The half-maximum distance η must be taken northerly in the northern hemisphere and southerly in the southern hemisphere. For the other half-maximum distance,

$$-k_2'(a) = \frac{a}{2b}\left[1 - \left(\frac{3b - 1}{b - 1}\right)^{1/2}\right]. \tag{19}$$

Values of $k_2'(a)$ as a function of I and β are given in Figure 4.

The ratio of half-maximum distances is given by

$$\eta_2 : \eta_2' = [(3b - 1)^{1/2} - (b - 1)^{1/2}]/[(3b - 1)^{1/2} + (b - 1)^{1/2}] \tag{20}$$

and is plotted in Figure 5. This enables us to compare the measured ratio with a theoretical value and thus see the degree of approximation obtained.

The reflection at the origin for the southern hemisphere anomaly profiles is shown easily for this case.

The shift of the anomaly peak from a position directly above the source is in the negative y-direction and of amount

$$\alpha_2 = (b - 1)/a, \tag{21}$$

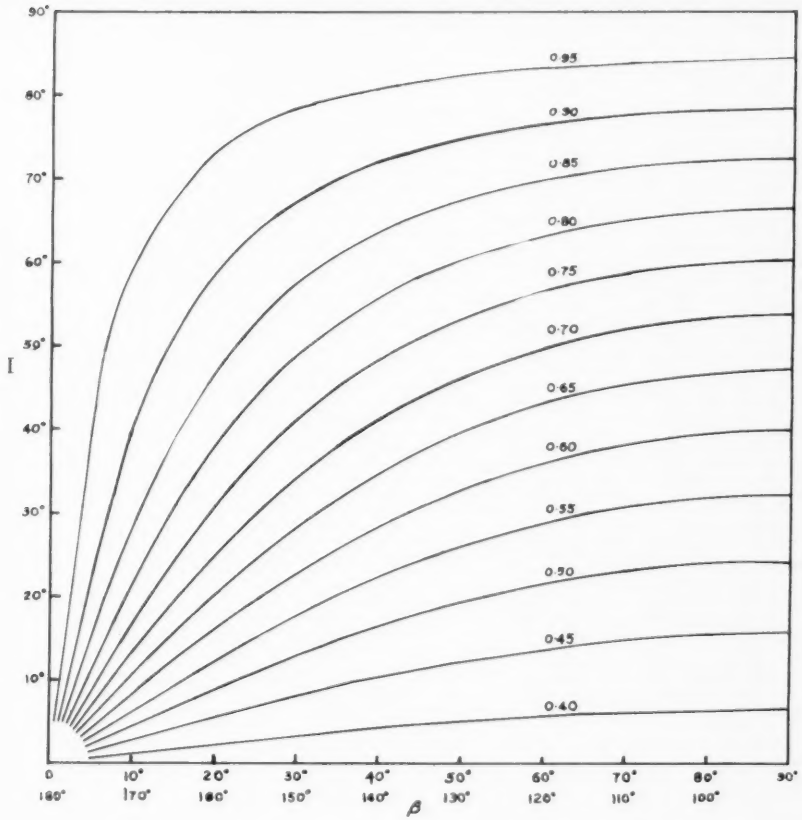

FIG. 4. Curves of constant total intensity depth factor $k_2'(a)$ for line source.

and the peak value

$$\Delta T_{\max} = \frac{2m_1 \sin I}{\zeta} \frac{1 - a\alpha_2}{1 + \alpha_2^2} \tag{22}$$

where m_1 is the pole strength per unit length.

POINT DIPOLE APPROXIMATION

We assume a dipole moment p_0 in the direction of the earth's field at a depth ζ below the plane of observations (Figure 6). The anomalous magnetic potential in the northern hemisphere for a meridional profile passing directly over the

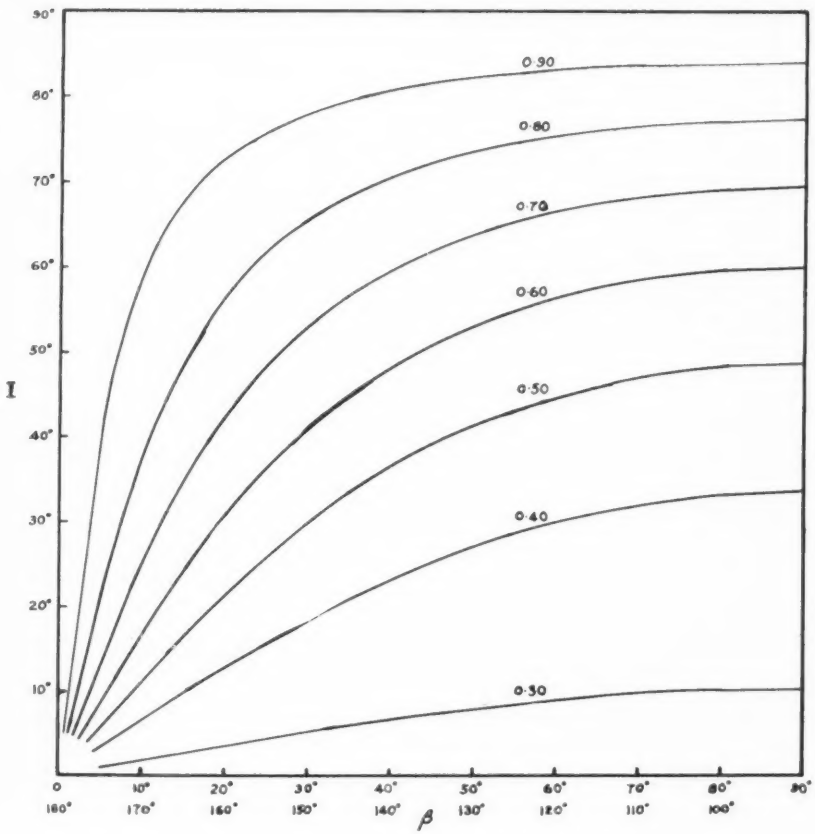

FIG. 5. Curves of constant ratio of half-maximum distance $\eta_2:\eta_2'$ for line source.

source is then

$$\Delta V_3 = p_0 \frac{y \cos I - \zeta \sin I}{(y^2 + \zeta^2)^{3/2}} . \tag{23}$$

Expressed in units of depth, the total intensity anomaly is

$$\Delta T_3 = f_3(\alpha) p_0 / \zeta^3 \tag{24}$$

where

$$f_3(\alpha) = (3 \sin^2 I - 1) - 6 \sin I \cos I \cdot \alpha + (3 \cos^2 I - 1)\alpha^2/(1+\alpha^2)^{5/2}. \tag{25}$$

From this expression, $f_3(\alpha)$ has been calculated for representative values of I

and the results presented in Figure 7. The mirror images in y of these curves are suitable for application in the southern hemisphere.

To determine the shift of anomaly maximum from the position directly above the source, we set

$$\frac{\partial}{\partial \alpha}(\Delta T) = 0, \quad \text{i.e.}$$

$$(3\cos^2 I - 1)\alpha^3 - (8 \sin I \cos I)\alpha^2 + (7 \sin^2 I - 3)\alpha + 2 \sin I \cos I = 0. \quad (26)$$

The negative real root of this equation yields the required value $-\alpha_3$ at the

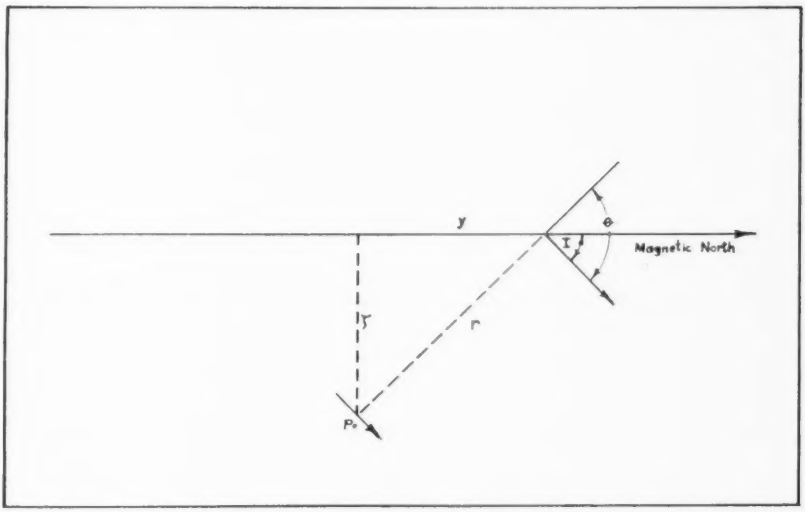

FIG. 6. Geometry of the dipole approximation.

anomaly maximum. This has been calculated for a number of values of I and the results given in Figure 8.

The half-maximum depth factors $k_3(a)$ and $k_3'(a)$ were obtained for various values of I by calculating the maximum value $f_3(-\alpha_3)$. Half of this value is then substituted in the expression for $f_3(\alpha)$ and the resulting equation solved for two real roots β_3 and $\beta_3'(\beta_3 > \beta_3')$. Then

$$k_3(a) = (\beta_3 + \alpha_3)^{-1}, \qquad k_3'(a) = -(\alpha_3 + \beta_3')^{-1}, \qquad (27)$$
$$\eta_3 : \eta_3' = -(\beta_3 + \alpha_3)/(\alpha_3 + \beta_3').$$

These factors are given in Figure 8.

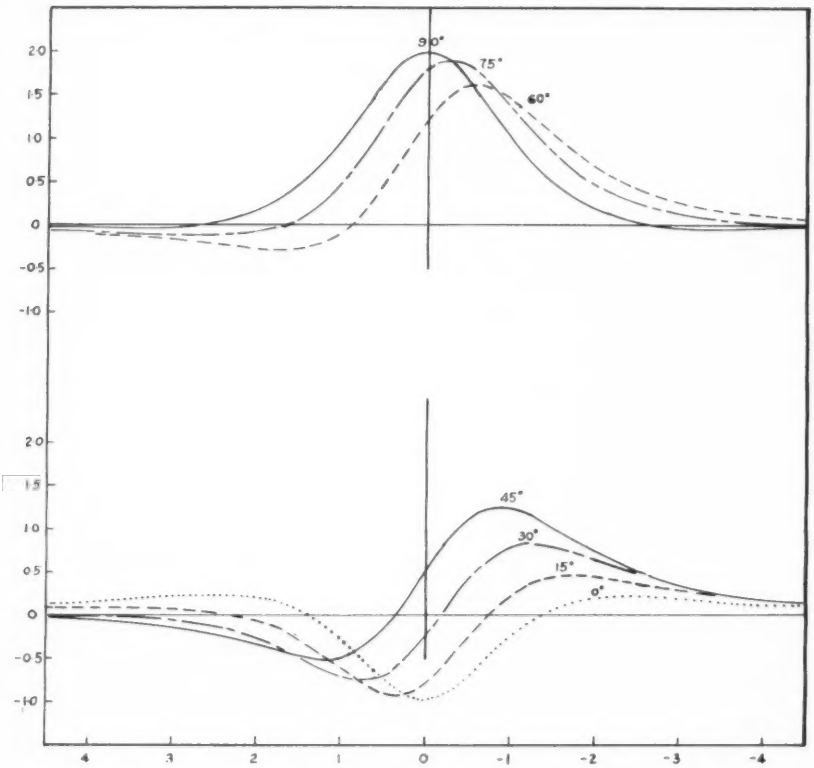

FIG. 7. Total intensity anomaly from a dipole source at various geomagnetic latitudes (northern hemisphere). Profiles in units of depth along magnetic meridian. ΔT is in units of p_0/ζ^3.

LINE OF DIPOLES

Consider a line of magnetic dipoles at depth ζ whose dipole moment is p_1 per unit length in the direction of the earth's field and which strikes at an angle β with magnetic north. We have for the magnetic potential in the northern hemisphere

$$\Delta V_4 = 2p_1[y \cos I \sin \beta + (z - \zeta) \sin I]/[y^2 + (\zeta - z)^2], \qquad (28)$$

when the y-direction is normal to strike and positive in the northerly half-plane. The total intensity anomaly for a profile along the y-axis is given by

$$\Delta T_4 = 2p_1 \cos^2 I \sin^2 \beta f_4(\alpha)/\zeta^2 \qquad (29)$$

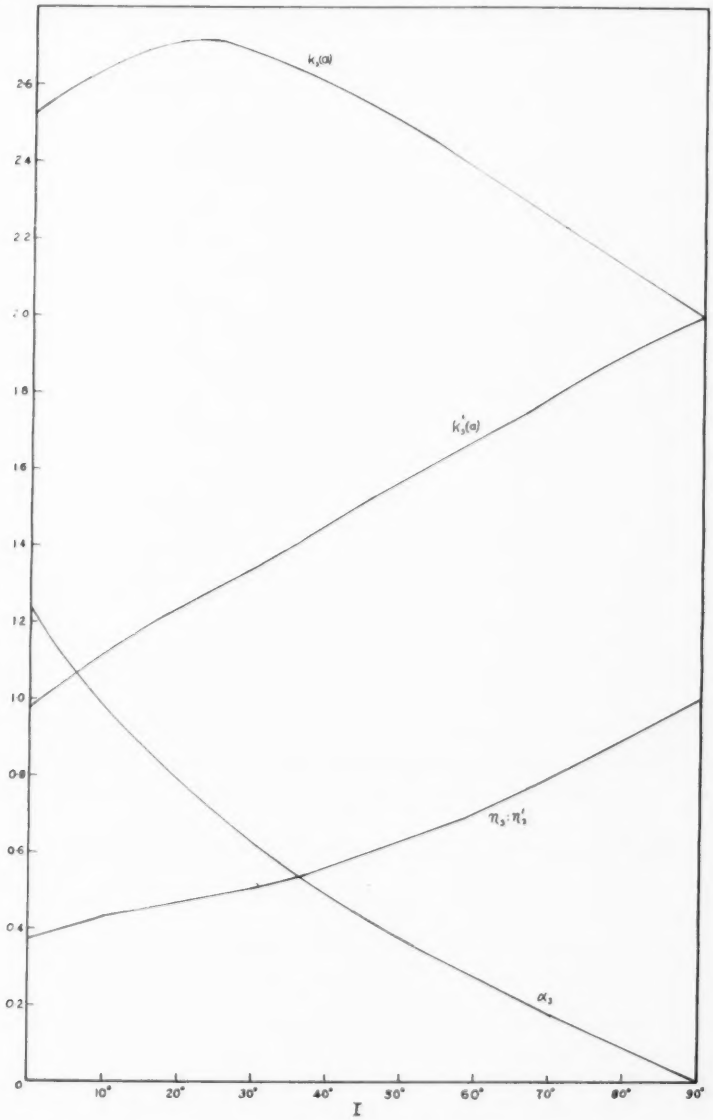

FIG. 8. Total intensity depth factors $k_3(a)$ and $k_3'(a)$, half-maximum distance ratio $\eta_3:\eta_3'$ and peak displacement α_3 for dipole source.

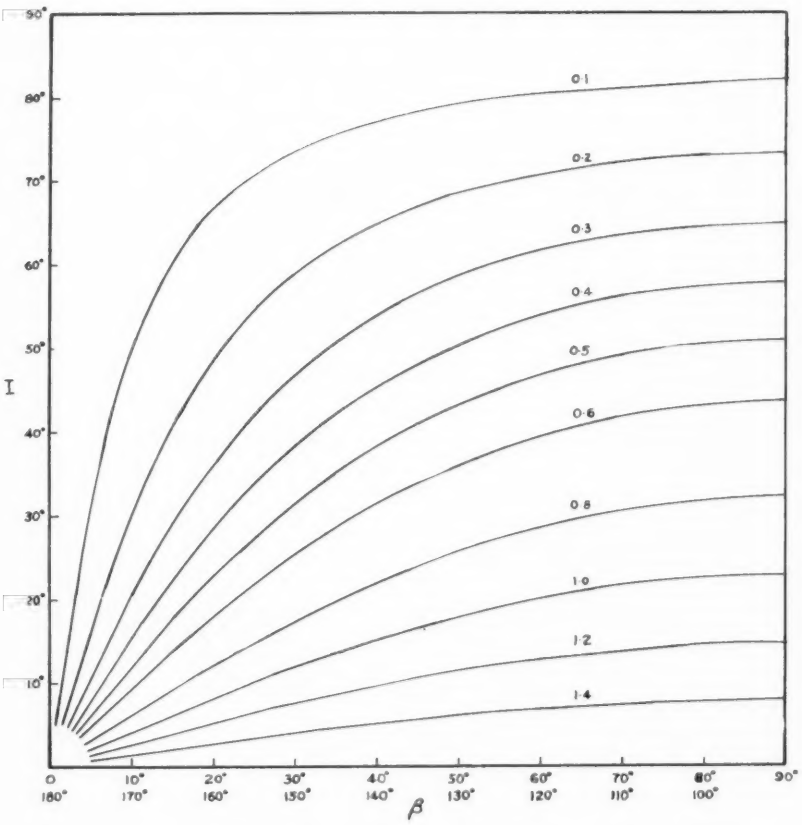

FIG. 9. Curves of constant shift of anomaly maximum α_4 in units of depth, line of dipoles source.

where

$$f_4(\alpha) = [(\alpha^2 - 1)(1 - q^2) - 4\alpha q]/(1 + \alpha^2)^2 \tag{30}$$

and

$$q = \tan I \csc \beta = a^{-1}. \tag{31}$$

The method of calculation of the half-maximum depth factors is the same as for the point dipole, the parameter used being q. Families of curves of constant q are used to show the factors in the same manner as for the line of poles. The results for α_4, $k_4(a)$, $k_4'(a)$ and $\eta_4{:}\eta_4'$ are shown in Figures 9, 10, 11 and 12, respectively.

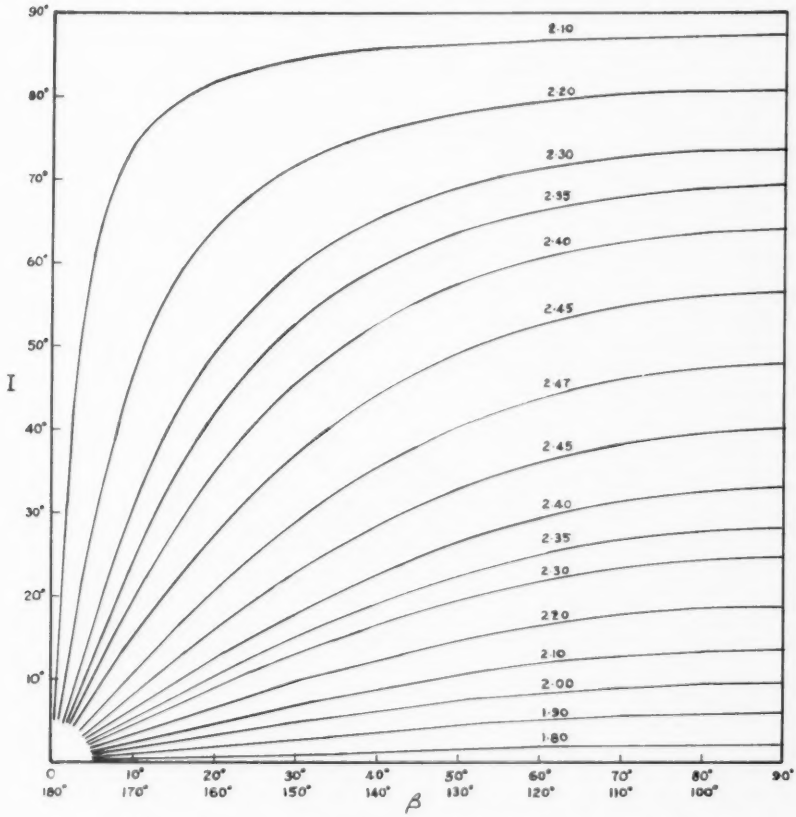

FIG. 10. Curves of constant total intensity depth factor $k_4(a)$ for line of dipoles source.

APPLICATIONS

Two field cases will be used as examples of the application of methods outlined in this paper. The first is from a survey in a high northern geomagnetic latitude, the Campbellford area of Canada, and is designated the Marmora Anomaly. The effect of line spacing on the detection of this anomaly has recently been discussed by Agocs (1955). Data were taken with a Gulf airborne magnetometer and published by the Geological Survey of Canada as Aeromagnetic Sheet No. 31 C/5, Campbellford. A copy of a portion of this map appears as Figure 13.

The anomaly minimum is weak, so a pole approximation is used. The elongation of the contours is not too pronounced, so the point pole model was first

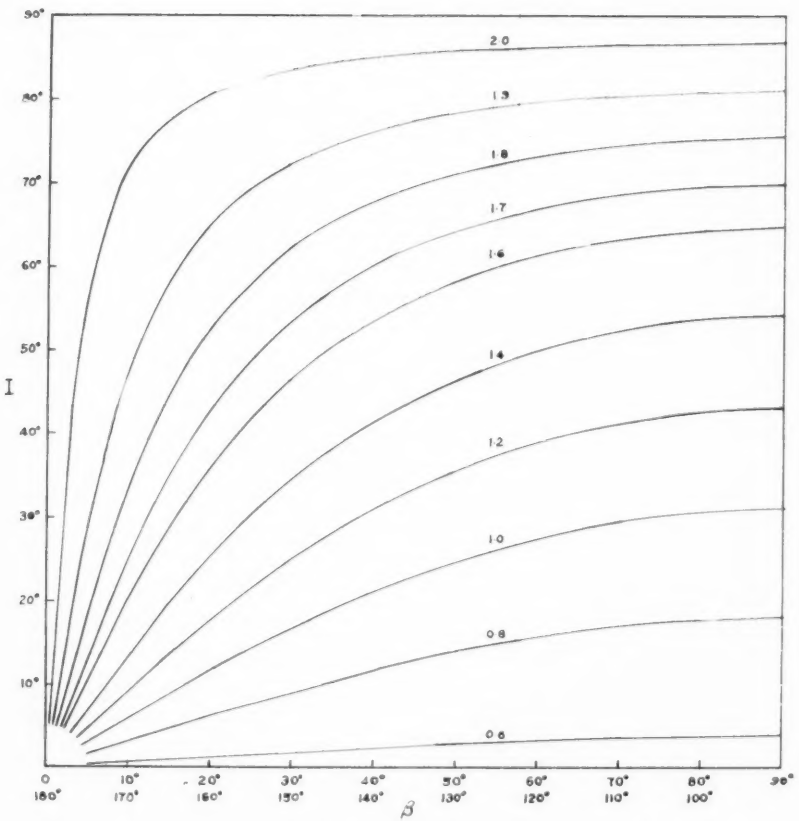

FIG. 11. Curves of constant total intensity depth factor $k_4'(a)$ for line of dipoles source.

tried. Along the magnetic meridian (dotted line) we have distances from anomaly maximum to half-maximum in both north and south directions of 910 feet, indicating a ratio $\eta:\eta'=1$ as opposed to the theoretical value for the point pole of 0.88 when $I=75°$ (Figure 2). Estimated depths are $\zeta_1=k_1(a)\eta=1{,}270$ ft from the northerly distance η and $\zeta_1'=k_1'(a)\eta'=1{,}110$ ft from the southerly η^1. If we assume a line of poles striking at $\beta=45°$ as indicated by the trend of the contours, we have (solid profile) $\eta=580$ ft, $\eta'=700$ ft, $\eta:\eta'=0.82$, the theoretical value (Figure 5, $I=75°$, $\beta=45°$). Thus this approximation seems more suitable. The estimated depths are then $\zeta_2=k_2(a)\eta=630$ ft (Henderson and Zietz, 1948, Figure 4), $\zeta_2'=k_2'(a)\eta'=630$ ft (this paper, Figure 4).

The magnetic ore mass causing this anomaly is 2,400 ft long, 500 ft wide at its maximum width, with a northwest-southeast strike and a dip southwest of 70°

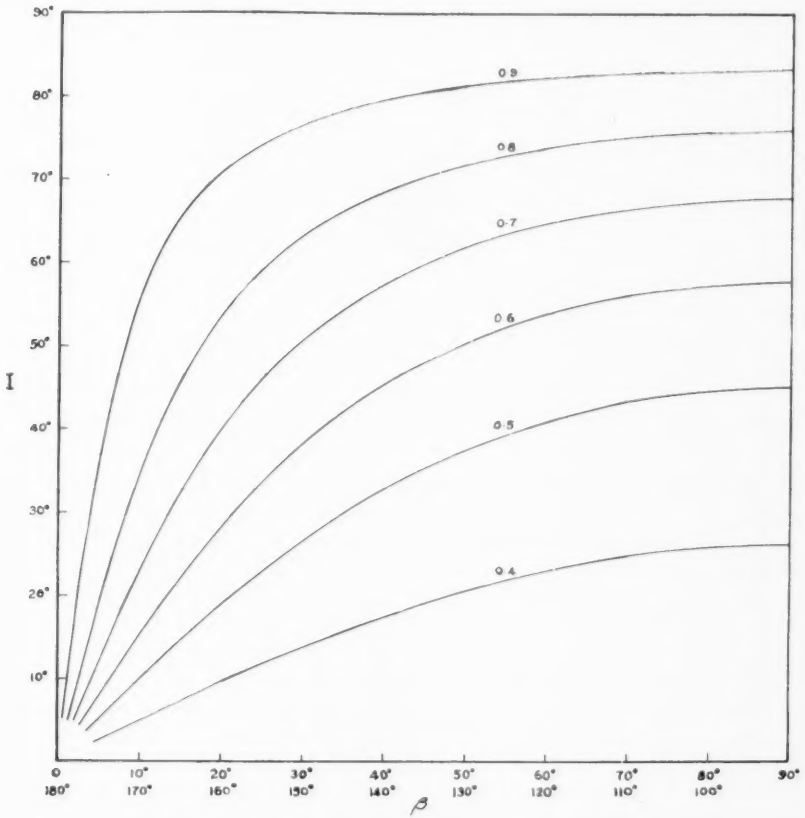

FIG. 12. Curves of constant ratio of half-maximum distances $\eta_4 : \eta_4'$ for line of dipoles source.

to 80°. It is capped by 120 ft of limestone, which added to the flight elevation gives the depth to the top of about 620 ft. From the configuration and depth of the source, the line of poles would be a suitable geophysical representation of it, as is shown by the agreement between estimated and actual depths. The width of the body would tend to broaden the anomaly slightly in this case, but its finite length would have a narrowing effect.

The second example is from a survey in a low southern geomagnetic latitude, the Katherine-Darwin region of Australia, and is designated Brown's Anomaly. This aeromagnetic anomaly, located southwest of Brown's Deposit, Rum Jungle, Northern Territory, appears on the contour map of Figure 14. This was compiled from data obtained using an AN/ASQ-1 magnetic airborne detector at

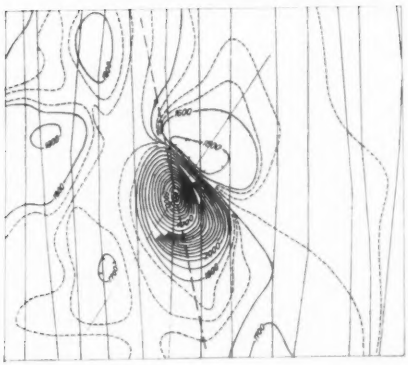

FIG. 13. Total magnetic intensity map showing the Marmora anomaly, a portion of Geological Survey of Canada Aeromagnetic Sheet No. 31 C/5, Campbellford. Scale one inch equals one mile. Flight lines shown.

an average height of 500 ft above terrain and supplied by the Bureau of Mineral Resources, Geology and Geophysics of the Commonwealth of Australia. Although the anomaly profile changes along strike in distances comparable with the

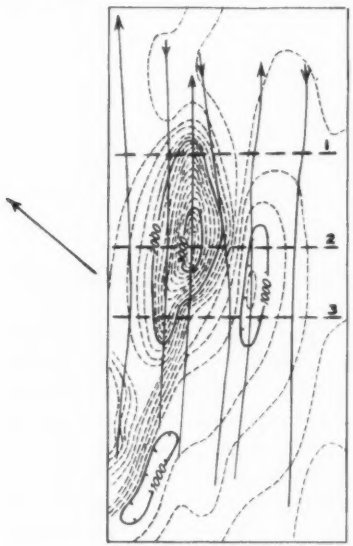

FIG. 14. Total magnetic intensity map showing Brown's anomaly, Rum Jungle, Northern Territory. Figure provided from an airborne magnetometer compilation sheet by the Bureau of Mineral Resources, Geology and Geophysics of the Commonwealth of Australia. Scale one inch equals one mile. Flight lines shown.

"half-width" of the anomaly, it was considered useful to measure the half-maximum distances on three representative profiles along the anomaly. These are indicated on Figure 14. We find "half-widths," the distances between half-maximum values, on profiles 1, 2, and 3 of 1,320, 1,320 and 990 ft approximately, indicating decrease in either depth or width to the southwest.

On profile no. 1, $\eta = 500$ ft, $\eta' = 820$ ft, hence $\eta : \eta' = 0.61$ which is above the theoretical value 0.47 for a line of poles at $\beta = 120°$, $I = 40°$ (Figure 5). The anomaly minimum is not pronounced, favouring the line of poles. From the two half-maximum distances, estimated depths are $\zeta_2 = 670$ ft, $\zeta_2' = 520$ ft. Using the total half-width, $\zeta_2'' = 570$ ft, indicating that the top of the magnetic body comes close to the surface. On profile no. 2, $\eta : \eta' = 0.8$, rather high for a line approximation, but would correspond to a line of vertical dipoles. For this case, the depth to the center was found to equal the half-width, i.e., 1,320 ft. Profile no. 3 also has a high $\eta : \eta'$ ratio, 0.7 half-width = 990 ft = depth to center for a line of vertical dipoles.

Subsequent ground magnetic work showed a vertical magnetic intensity profile fairly simple to the northeast but developing a double peak to the center giving rise to the increased apparent depth. Drilling at the center revealed a pyrrhotite-bearing body coming close to the surface.

In measuring the η's in both these cases, the half-maximum value is of course taken as the median value between the intensity of anomaly maximum and the general level in areas away from the anomaly. Choice of the latter is somewhat arbitrary, the actual values selected being 1,700 γ for the Marmora anomaly and 1,300 γ for Brown's anomaly.

A further point of interest is the question of line spacing in order to detect sources of limited extent at a given depth. It appears that the point pole would offer a common case, and it is easily seen from equation (13) that for (magnetic) north-south flight lines, the probability of recording an anomaly from a point source with maximum at least one-half the absolute anomaly maximum is given by $P = 1.53(1+\alpha_1^2)^{1/2}\zeta/S$ where S is the flight-line spacing and ζ the depth to the source.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the suggestions for revision of this paper made by Professor J. C. Jaeger. Grateful acknowledgment is due to the Director of the Geological Survey of Canada for permission to use the compilation sheet shown as Figure 13 and to the Director of the Bureau of Mineral Resources, Geology and Geophysics of the Commonwealth of Australia for the compilation sheet shown as Figure 14.

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GEOPHYSICS, VOL. XXI, NO. 4 (OCTOBER, 1956), PP. 1041-1046, 2 FIGS.

GRAPHICAL SCALES FOR MAPPING POTENTIAL FUNCTIONS*

IRWIN ROMAN†

ABSTRACT

Graphical scales can be prepared and used for rapid determinations of potential field values which depend only on the distances between two fixed points. The method can be applied to determine the potential at the surface of a homogeneous earth due to a current pole at its surface, and to the potential at the surface of the earth considered as an infinite insulator separated from the surface by a parallel plate of finite resistivity. Portions of two typical scales and two sets of equipotential curves drawn by use of the scales are shown.

If the value of a function can be determined by the distance between two points and if the required accuracy justifies the use of graphical methods, strip scales have proved adequate, simple, and rapid for measurement. For occasional use, especially if a single pair of points is involved in each determination, the distances may be measured and the functional values taken from a table or calculated directly. However, in problems involving potentials, there are usually two or more sources whose contributions are added algebraically, so that scales are much simpler to use than the process of scaling, table entry, and addition.

Two such scales are illustrated in Figure 1. The "normal" scale is for use on the surface of a homogeneous half-space bounded by the plane of the map. A current pole is assumed to lie in this plane at the pivot point of the scale, indicated by $\oplus$. The point at which the potential is sought lies in the plane of the map, directly under the edge of the scale. The scale shows the value of the potential at that point except for a constant factor depending on the units used. The "insulating" potential scale shows the corresponding potential value when a plane half a unit below the plane of the map separates the upper layer from an infinite space that is a perfect insulator.

To use the scales for reading potentials due to a pair of poles, the scales should be prepared in duplicate. One scale is pivoted at each pole. For the usual case of equal and opposite poles, the algebraic sum of the two scale readings is the potential at that point due to the two poles, except for units. For other combinations of poles, additional scales can be drawn, or the unit lengths can be changed to correspond to the values of the separate pole strengths.

The scales can also be used to plot an equipotential curve by adjusting one of the scales until the difference in readings of the two scales has the desired value, or until the algebraic sum of the various scale readings has the desired value. Two sets of equipotential curves are shown in Figure 2. In this figure a

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† U. S. Geological Survey.

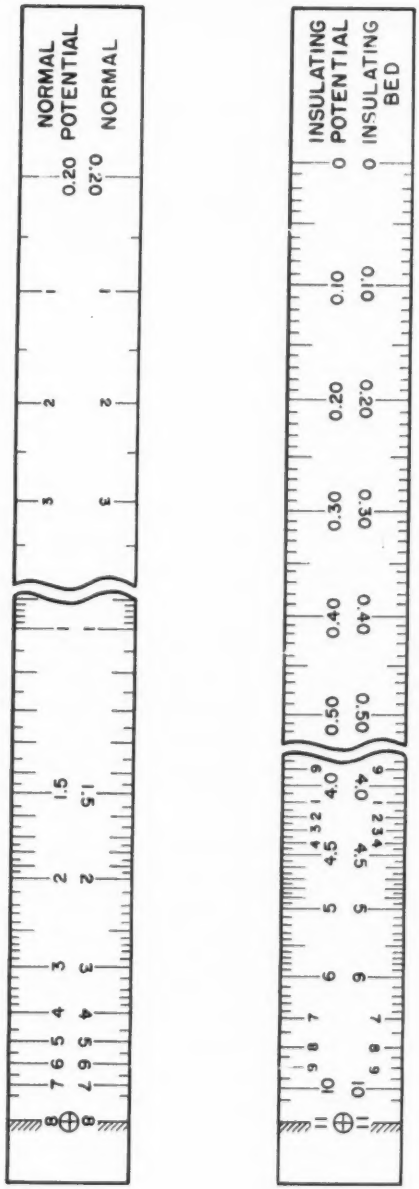

FIG. 1. Portions of two typical scales.

unit positive pole was assumed at the left and a unit negative pole at the right, separated by a distance of three units with both poles in the map plane. The left half shows the curves for a normal, homogeneous earth, and the right half shows the curves for an earth in which an infinite bed is separated from the overburden by a plane half a unit deep.

In preparing the curves of Figure 2, two hand-drawn scales were used for each set. Individual lines of the scale were considered as being within about one-

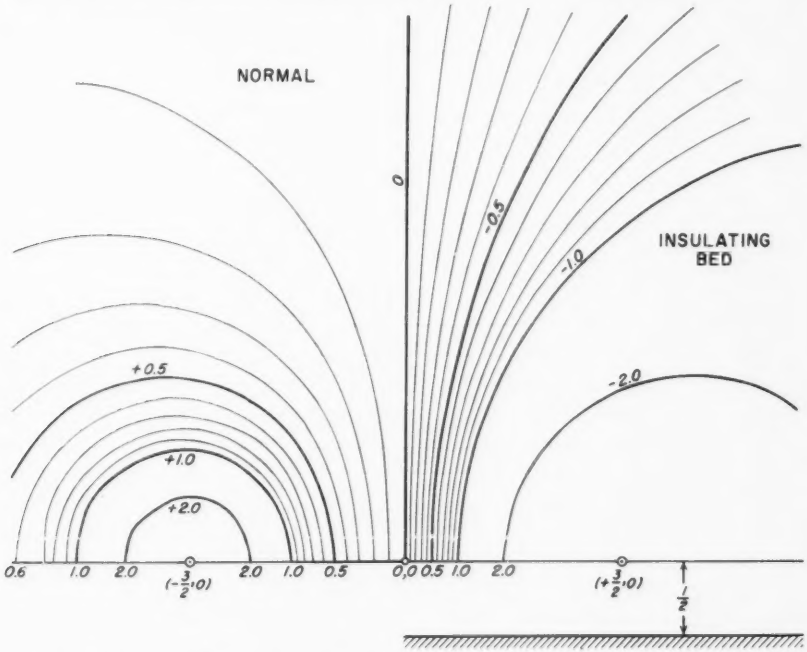

FIG. 2. Equipotential curves plotted with scales. Left side for homogeneous earth. Right side for a perfectly insulating earth underlying an overburden half a unit thick and not perfectly insulating.

fiftieth of an inch of their calculated positions. The two sets of curves were drawn in less than three hours, without previous experience and with many more points plotted than needed to determine the curves.

To illustrate the method of constructing the scales, consider the problem of the electrical potential. For a homogeneous earth, the potential at the surface due to a current source of strength I at a distance l from the point is given by

$$V = (I\rho/2\pi)(1/l)$$

where ρ is the resistivity of the earth. The function shown on the scales is

$$U = (2\pi/I\rho)V = 1/l.$$

Accordingly, the scale readings must be multiplied by $(I\rho/2\pi)$ to give the potential value.

For an earth separated into two homogeneous portions by a horizontal plane, the function to be plotted is less simple. The problem has been solved (Roman 1931) and tables are available for 20 ratios of the bed resistivity to the overburden resistivity and for distances not more than ten times the thickness of the overburden. The function to be plotted is

$$U = 1/l + W/h$$

where h is the thickness of the overburden and W is taken from the published tables. An additive constant is permissible. In the lower scale of Figure 1, the values have been increased by three to avoid negative numbers. For this scale, the reading for a single pole must be decreased by three, but the constant disappears for an equal and opposite pair of poles.

The drawing must have the same unit of length as that used in the scales. Multiplication by a constant factor can correct for current strength, resistivity, and units used. For low accuracy, the use of the scales is direct. For higher accuracy, the scales can be used to furnish a first approximation from which the more accurate value can be determined.

In constructing the scales, two methods are convenient. In one method, values of l are calculated, for selected values of U, using interpolation in the W tables, and intermediate values are estimated. In the second method, a curve is drawn showing values of U for tabulated values of l and from this curve values of l corresponding to selected values of U are read.

The scales may have any of several forms. For transparent strips, the scale can be drawn down the center of the strip, passing through the pivot. In this form the scale readings should be shown direct and reversed, so that one set will be direct in any position of the scale. The width of the scale is not critical. For opaque scales, a slot can be cut along the strip, instead of the line. However, for opaque scales, it is simpler to draw the scale on each edge of the strip, remembering that the value of l is the distance from the pivot to the point of the edge. The values should be shown oppositely on the two edges, so that one set is always in position for direct reading. The user then has a choice of four combinations of scales to use for each point.

In the interest of brevity and directness, the discussion has been restricted to a single application. An exhaustive listing of possible extensions would carry the discussion into many branches of engineering and applied mathematics. The following aspects of the problem are presented for more detailed consideration.

1. The unit of length has been selected so that the upper layer, if the medium is not homogeneous but consists of a single "overburden" layer, has a thickness of one-half unit. This reduces the fun tion to be plotted to

$V = 2W + 1/l$ and does not result in a loss of generality, as the unit is arbitrary and must be adjusted in each analysis of observations.

2. For the specific scales discussed, the published tables extend in l from zero to five, or ten times the thickness of the upper layer. For some applications, only a part of the range is needed; for others the tables may need to be extended.
3. The basic method is applicable to any problem in which the desired function can be reduced to a combination of values each of which depends on a map distance and on constants for the scale used. As a prerequisite, the function must be determinable by graphs, tables, calculation or other suitable means.
4. The scales can be used only for analyses for which their source, such as a table, can be used. The advantage of the scales lies in the speed and convenience of their use, after they have been constructed. Two of their disadvantages are a loss of accuracy due to graphical use and the necessity of preparing a scale for each class of problems to be investigated. For an occasional use, there may be an increase in the time required, but each additional use after the first represents a reduction in the relative time and cost of their preparation.
5. The text shows two scales used in the resistivity problem. The "normal" scale applies to a homogeneous space or half-space and a pair of them could be used for the potential field due to two poles of equal strength, regardless of their signs, which must be considered in the reduction to an algebraic sum. The application to a current field requires opposite signs. The same scales could be used to determine the potential field of a magnetic dipole or to a field caused by two equal poles of the same sign. By multiplying the readings of one scale by a constant factor, either numerically or by preparing another scale, the field due to unequal poles can be analyzed. A set of scales such as those shown would consist of twenty pairs, one for each value of Q for which the values of W are available from the tables. Such a set could be used for various problems for which a single overburden is involved. The resistivity is obtained from differences in potential at two points of the field. The separation of the poles is arbitrary and the set of scales can be used for arbitrary arrangements of the two current poles and two potential stakes.
6. Although the example illustrates the mapping of a potential field, the scales could be used to determine various types of profiles along a selected path, which could be straight or curved, and which need not pass through either pole. For example, in one application of the single probe potential analysis, one current pole and one potential stake are located remotely from each other and the remaining two stakes. The potential of the area around the local current pole is measured. For interpretation, the measurements are corrected for the locations of the remote stakes and profiles in selected

directions are compared with theoretical profiles. For quick results, the scales are adequate. For more precise values, reference may be made to the tables, using the preliminary values as a guide.

7. To avoid negative scale readings, a constant may be added to the readings of each scale of the pair. This constant may have any value numerically larger than the largest negative value of the function over the length of the scale. In the difference of two readings, the constant disappears; for the sum, twice the value of the constant must be subtracted if the true value is needed. For example, in the scale illustrated for $Q=+1$, the constant must exceed 2.99; for $Q=+0.5$, the constant must exceed 0.82; for $Q=+0.2$, it must exceed 0.15; for $Q=+0.1$ and for negative values of Q, V is positive over the entire scale and no additive constant is needed. If a single constant for the entire set of scales is desired, the quantity three will suffice.
8. By using suitable functions to be shown on the scales, two dimensional problems may be analyzed and problems other than those of the potential may be analyzed. Each such problem must be considered separately.

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EXTRAPOLATION AND INTERPOLATION FORMULAE ADAPTABLE TO DESK AND OTHER TYPES OF DIGITAL COMPUTERS*

V. L. JONES†

ABSTRACT

The advent of high-speed digital computing machines requires extrapolation and interpolation methods which do not involve central differences and time-consuming tabular information. Extrapolation and interpolation formulae meeting these requirements are developed. These formulae are applicable to the desk calculator as well as to punched-card programming systems for electronic-digital computors. Some applications of the usefulness of these formulae are noted in connection with the preparation of gravity and magnetic maps. Their usefulness may likewise be extended to other types of geophysical and experimental data where the time required to obtain computed results is an economic factor.

INTRODUCTION

In the computation and processing of geophysical field results and other types of experimental data, it is often advantageous and sometimes necessary to extend some non-linear function beyond the limits of the data at hand. Likewise it is often desirable to establish some point on a curve which falls between two given datum values. There are various methods for extrapolating a given function for a short distance beyond the limits of the data, and the mathematical literature is replete with interpolation methods such as Newton's and Lagrange's formulae. These methods, however, involve central differences and the setting up of tabular information. This is a time-consuming procedure and does not lend itself well to the processing of geophysical and other types of experimental data where the time required for obtaining computed results is an economic factor. With the arrival of the various high-speed digital computing machines, the problem is all the more pressing for a method of extrapolation and interpolation which is adaptable to such devices as well as the desk calculator.

As an example requiring an extrapolation formula which is adaptable to computing machines, consider the preparation of regional gravity and magnetic maps. In the computation of regional values some method of averaging is usually employed. To facilitate this averaging process, templates on which circles, squares and other rectangular patterns have been constructed are used. The values to be averaged are taken from equally-spaced points on the circles, or at the corners of intersecting squares or triangles. The average of such values is usually placed at the center of the pattern. In such a method of preparation of regional data, a portion bordering the edge of the map will thus be void of regional values. This, of course, is due to the mechanical nature of the method. The same condition

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prevails in the preparation of first or second derivative gravity and magnetic maps.

In the preparation of total and regional gravity and magnetic maps it is often desirable to have a value for some point for which no field data are available, due to the fact that such point may be in a lake, river, or some other inaccessible portion of the terrain. With in-line data available on both sides of such an area, an interpolation formula adaptable to the computing machine is thus indicated. Again, it is sometimes desirable to remove an anomalous condition or a "sour" value from some particular datum on a map by interpolation of the data on each side of the point. These and many other examples call for extrapolation and interpolation formulae which can be readily used with desk calculators and other digital-computing machines.

It was the purpose of this investigation to derive mathematical expressions which could be employed to extrapolate and interpolate regional gravity and magnetic profiles, and at the same time lend themselves to computing devices. The problem of extrapolation will be taken up first.

EXTRAPOLATION FORMULAE

The ideal expression is one involving a set of weight factors say, which when multiplied by respective equally-spaced values at the end of the regional profile, and a summation taken, will give an additional value for the end of the profile. Then, using $n-1$ values of the profile plus the extrapolated value, one may obtain a second extrapolated value and so on.

The type of expression desired should be of the form

$$y = W_0y_0 + W_1y_1 + W_2y_2{}^{+++}W_{n-1}y_{n-1} + W_ny_n$$

where y_0, y_1, $y_2 \cdots y_n$ are successive equally-spaced values at the end of the profile, y_n being the terminal value. Another desirable feature is to have the expression contain a number of terms on the right so as to be universally applicable to all types of regional profile data.

If one assumes a linear extrapolation, the expression will have the form:

$$y = W_0y_0 + W_1y_1,$$

and the polynomial form will be

$$f(x) = y = a_0 + a_1x$$

then

$$f(x_0) \equiv y_0 = a_0$$

and

$$f(x_1) \equiv y_1 = a_0 + a_1$$
$$f(x_2) \equiv y_2 = a_0 + 2a_1.$$

Now,

$$W_0y_0 + W_1y_1 = y_2$$

or,

$$W_0(a_0) + W_1(a_0 + a_1) = a_0 + 2a_1$$

from which $W_1 = 2$; and $W_0 = -1$; and the linear extrapolation formula takes the form

$$y = -y_0 + 2y_1. \tag{1}$$

Now if one assumes a second-degree extrapolation curve, the formula will be

$$y = W_0y_0 + W_1y_1 + W_2y_2$$

and the weight factors represented by the W's can be evaluated in a similar manner. They are as follows: $W_0 = 1$; $W_1 = -3$; $W_2 = 3$.

The extrapolation formula is then

$$y = y_0 - 3y_1 + 3y_2. \tag{2}$$

A third-degree extrapolation curve will be

$$y = W_0y_0 + W_1y_1 + W_2y_2 + W_3y_3$$

from which the W's are found to be: $W_0 = -1$; $W_1 = 4$; $W_2 = -6$; $W_3 = 4$. The extrapolation formula is thus

$$y = -y_0 + 4y_1 - 6y_2 + 4y_3. \tag{3}$$

In a like manner the weight factors for a fourth-degree curve will yield the following values: $W_0 = 1$; $W_1 = -5$; $W_2 = 10$; $W_3 = -10$; $W_4 = 5$; and the extrapolation formula is seen to be

$$y = y_0 - 5y_1 + 10y_2 - 10y_3 + 5y_4. \tag{4}$$

In passing from a linear to successive higher-order curves, one immediately recognizes the sequence of the binomial coefficients in the W's.

During the progress of this investigation eight independent profiles were selected from two different geological areas, making a total of sixteen independent profiles for experimental purposes. In all cases it was found that a parabolic function of the polynomial form

$$y = a_0 + a_1x + a_2x^2$$

was best suited to represent the regional gravity profiles.

A second approach to the problem now presents itself. Let it be required to find a least square solution of a second-degree curve using four points of the profile to predict the fifth point. Then the polynomial will be as usual

$$y = a_0 + a_1x + a_2x^2$$

and

$$f(x_0) - y_0 = a_0 + a_1x_0 + a_2x_0^2 - y_0 = \delta_0$$
$$\cdot \quad \cdot = \cdot \quad \cdot \quad \cdot \quad \cdot = \cdot$$
$$\cdot \quad \cdot = \cdot \quad \cdot \quad \cdot \quad \cdot = \cdot$$
$$f(x_3) - y_3 = a_0 + a_1x_3 + a_2x_3^2 - y_3 = \delta_3.$$

To obtain a least square solution the

$$\sum_{i=0}^{3} \delta_i^2$$

must be a minimum, and

$$\frac{\partial S}{\partial a_0} = \frac{\partial S}{\partial a_1} = \frac{\partial S}{\partial a_2} = 0$$

where

$$S = \sum_{i=0}^{3} \delta_i^2.$$

Solving for the a's in terms of y_0, y_1, and y_2, one finds that

$$a_0 = .95y_0 + .15y_1 - .15y_2 + .05y_3$$
$$a_1 = -1.05y_0 + .65y_1 + .85y_2 - .45y_3$$
$$a_2 = .25y_0 - .25y_1 - .25y_2 + .25y_3.$$

On substituting these values for the a's back in the original equation, and solving for the extrapolated value y_4, where $x = x_4 = 4$, one obtains

$$4y = 3y_0 - 5y_1 - 3y_2 + 9y_3 \tag{5}$$

or

$$y = .75y_0 - 1.25y_1 - .75y_2 + 2.25y_3 \tag{5a}$$

as the extrapolation formula.

By forcing the extrapolation curve to pass directly through the last point of the profile data, a third method of obtaining a second-degree curve is available. By so doing, δ_3 becomes zero at the coordinates (x_3, y_3) and

$$y_3 = a_0 + 3a_1 + 9a_2$$

from which a_0 is pre-determined, and is

$$a_0 = y_3 - 3a_1 - 9a_2.$$

Using this value for a_0 in setting up the values for the δ_3^2 and proceeding as in the previous case, one finds the extrapolation formula to be

$$19y = 12y_0 - 17y_1 - 21y_2 + 45y_3 \tag{6}$$

or

$$y = .63y_0 - .89y_1 - 1.10y_2 - 2.37y_3. \tag{6a}$$

This is a restricted least square solution for the second-degree curve employing the last four values of the profile, in that the curve is forced to pass through the last profile datum point.

The first solution to the problem discussed above in which a second-degree curve is obtained, namely equation (2), is also a least square solution to the problem employing only the three end profile values, since it takes only three points to uniquely define a second-degree equation.

The three extrapolation formulae outlined above, equations (2), (5), and (6), each of which represents a second-degree polynomial, were applied to the sixteen independent profiles, and errors tabulated for the first, second, third and fourth extrapolated points. The values of these errors are set out in the accompanying table.

The results obtained from these sixteen profiles indicate that the second-degree curve employing only three weight factors applied to the three end values of a profile yield the best over-all results for extrapolation purposes. It will also be noted from the data that it is safe to extrapolate three additional points for a profile using equation (2), and not have the third extrapolation point in error by more than four gravity units. In addition it will also be noted that the simplicity of this equation is superior to that of equations (5) and (6) in its adaptation to the various types of computing devices and the desk calculator.

FOUR GROUPS OF FOUR EACH INDEPENDENT PROFILES
FIRST TWO GROUPS FROM OTTAWA COUNTY, KANSAS
LAST TWO GROUPS FROM MISSISSIPPI

3W $y=y_0-3y_1+3y_2$				2° L. S. Curve $4y=3y_0-5y_1-3y_2+9y_3$				2° L. S. Curve—last point restricted to datum point $19y=12y_0-17y_1-21y_2+45y_3$			
Errors				Errors				Errors			
4th	3rd	2nd	1st	4th	3rd	2nd	1st	4th	3rd	2nd	1st
+.20	+.18	+.08	+.03	+.26	+.19	+.10	+.04	+.26	+.19	+.10	+.04
+.20	+.10	+.05	+.02	+.36	+.20	+.10	+.04	+1.09	+.45	+.09	−.15
+.11	+.11	+.07	+.03	+.05	+.07	+.05	+.02	+.05	+.07	+.05	+.02
+.23	+.10	+.04	+.02	+.13	+.03	0.00	0.00	+.07	0.00	−.01	0.00
+.23	+.12	+.06	+.01	+.29	+.16	+.08	+.02	+.29	+.16	+.08	+.02
−.27	−.14	−.04	0.00	−.21	−.10	−.02	+.01	−.21	−.10	−.02	+.01
+.17	+.07	+.02	−.01	+.33	+.17	+.07	+.01	+.23	+.11	+.04	0.00
+.40	+.22	+.10	+.04	+.18	+.08	+.03	+.01	+.20	+.09	+.03	+.01
+.39	+.14	+.06	−.02	+.33	+.10	+.04	+.01	+.33	+.10	+.04	+.01
−.53	−.27	−.08	0.00	−.37	−.17	−.03	+.02	−.47	−.33	−.06	+.01
−.10	−.10	−.08	−.03	−.16	−.14	−.10	−.04	−.16	−.14	−.10	−.04
−.76	−.39	−.16	−.03	−.70	−.35	−.14	−.03	−.70	−.35	−.14	−.02
+.14	+.06	+.04	+.01	+.20	+.10	+.06	−.02	+.20	+.10	+.06	+.02
+.07	+.16	+.19	+.15	−.19	−.01	+.10	+.11	−.20	−.01	+.10	+.11
+.41	+.20	+.09	+.02	+.41	+.20	+.09	+.02	+.47	+.24	+.11	+.03
+.05	0.00	−.02	−.01	+.28	+.14	+.05	+.02	+.25	+.13	+.05	+.02

Note—Errors are in milligals.

INTERPOLATION FORMULAE

A little reflection reveals that by suitable manipulation of the algebra involved, the above extrapolation formulae may be reconstructed for interpolation purposes. Such formulae would be quite useful in gravity and magnetic work where a value is desired for some particular point on a map which has given values on either side.

Since in its present form, equation (5a) is useful for extrapolation purposes only, the desirability for having a similar expression for interpolation purposes becomes apparent. For example, suppose that a value is desired for the point P in the following profile illustration:

90	91	92	P	94	95	96
*	*	*	*	*	*	*
1	2	3	4	5	6	7

in which there is no value available for the fourth point as shown. This condition occurs quite often in gravity and magnetic mapping.

Now, let it be required that a formula of the type

$$y = W_0y_0 + W_1y_1 + W_2y_2 + W_3y_3$$

be derived for interpolating the value of P by using the available data of the points on each side of P. Since only four points are required in equation (5) to extrapolate a fifth point, let it likewise be required to use only four points to interpolate a value for P.

Remembering in the solution for a_0, a_1, a_2 as given above, the x values are equally-spaced intervals; they must, therefore, be equally-spaced intervals in the interpolation expression. This can be accomplished in the above illustration by choosing points 1, 3, 5, and 7 and denoting them respectively as y_0, y_1, y_2, and y_3. When this is done, the point P becomes $y=1.5$, for which the value of the x interval is likewise 1.5. On substituting the values of the a's (as determined in the extrapolation problem) back into the original equation

$$y = a_0 + a_1x + a_2x^2$$

and assigning the value of 1.5 for x, one obtains

$$y = -.06y_0 + .56y_1 + .56y_2 - .06y_3 \qquad (7)$$

as the interpolation formula for the mid-point P. On substituting the values for the above illustration, $y_0=90$; $y_1=92$; $y_2=94$; $y_3=96$; the interpolated value for the point P is found to be 93. This, of course, is in agreement with the linear assignment of values used in the illustration.

The only restriction placed on this particular interpolation formula is: the value sought by interpolation must be the mid-point of a curve which is defined by four equally-spaced values.

By applying the above procedure one may also obtain interpolation formulae for various equally-spaced values, the interpolated value, of course, is always

for the mid-point. In the case that the number of values defining the curve is an even number, the interpolated value will be for a point half way between the two middle values expressing the curve, as illustrated in the above example. In the case that the number of values defining the curve is an odd number, the interpolated value will be for the mid-point of the set of odd values.

A little reflection will reveal that there can be no interpolation formula for the mid-point of the curve which is defined by three equally-spaced values, since it takes a minimum of three points to define a second degree curve, and in this case the value for the mid-point would have to be available for defining the curve. Thus, if one endeavored to obtain a least square value for this mid-point, the interpolated value would simply result in obtaining the same value which was used to define the observed or experimental second-degree curve.

The interpolation formulae for curves employing five, six, and seven points are as follows:

5 points; $y = -.086y_0 + .343y_1 + .486y_2 + .343y_3 - .086y_4$ (8)

6 points; $y = -.093y_0 + .218y_1 + .375y_2 + .375y_3 + .218y_4 - .093y_5$ (9)

7 points; $y = -.09y_0 + .14y_1 + .29y_2 + .33y_3 + .29y_4 + .14y_5 - .09y_6$. (10)

When using an interpolation formula in connection with a gravity or magnetic map, one has a choice of the four formulae outlined above, as well as a wide latitude in the way the chosen formula is used. For example, one may use the four-point formula in connection with a seven-point profile as was done in the illustration. This would be advantageous in the case where one of the points was a "sour" value, or a one point anomalous value. Suppose that point 2 in the illustration had been 92 or 94 in value, by using the four-point formula it is eliminated from the interpolated least square value of the point *P*. If, on the other hand, it is found desirable to include an anomalous picture which is expressed by one or even two or more points, the seven-point formula may be used. In other cases the five or six-point formulae may be found to be more desirable.

Another valuable use may be found in an application of this method for interpolating mid-point values in connection with the preparation of a regional gravity or magnetic map. The profiles may be taken as one or more sets of orthogonal diameters of a circle, the point of intersection being the mid-points of each diameter or profile and the center of the circle. The interpolated mid-points may then be averaged and used as the regional value for the center of the circle. This procedure for computing near-surface and basemental effects is much simpler and less time consuming than the methods of surface fitting by orthogonal polynomials as described by Simpson (1954), and, Oldham and Sutherland (1955). It does, however, have an element of subjectivity, in that a knowledge of the depth to basement is required in order to make a proper choice of interval. Brown (1956) has treated the problem of minimum variance in surface fitting by orthogonal polynomials. Agocs (1951) has discussed the simplest case, that of a first order or

plane surface, in which he uses synthetic data. Equation 7 when used as orthogonal diameters of a circle yields a parabolic surface. A separate paper on the subject is in preparation.

Another useful application of the interpolation formulae is to be found in the preparation of geodetic tables, such as latitude and departure data, etc. There are also many other types of tabular information for which these formulae may prove to be quite valuable where calculating machines and desk computors are available for determining the interpolated values.

SUMMARY AND CONCLUSION

Equations (2), (5), and (6) are least square extrapolation formulae, while equations (7), (8), (9), and (10) are least square interpolation formulae. Each of these formulae is derived from the parabolic function

$$y = a_0 + a_1x + a_2x^2.$$

Equation (2) has been found to be quite satisfactory when used to extrapolate two or three additional points of a regional gravity or magnetic profile. Since, however, the primitive quadratic from which it is derived does not contain an inflection point, this formula will not extrapolate values beyond a point where there is a reversal in the gradient, i.e., a point of inflection. In this connection, an inspection of the data from which the regional is being derived will reveal areas in which the formula is not applicable.

Equation (7) has been found to be the most useful interpolation formula in gravity and magnetic mapping.

Interpolation formulae derived from a cubic and higher order primitives may be obtained similarly to that of equation (7).

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AN ELECTRICAL CREVASSE DETECTOR*

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ABSTRACT

Numerous fatal encounters with large crevasses concealed by bridges of drifted snow have occurred on the Greenland icecap and elsewhere. In response to an urgent need for rapid and reliable means of crevasse detection, a promising geophysical method has now been developed for the Department of Defense. This method is analogous to the four-electrode method of measuring earth resistivities. It is different in that an alternating dielectric displacement-current field is employed rather than a field of conduction current since the ice medium is essentially a nonconductor. As a result, basic differences in technique are necessary. The systems tested in Greenland and Antarctica, to date, which employ this method, continuously indicate or record the capacitive transfer reactance between pairs of electrode sleds or vehicles. Systems have been operated successfully while in motion at surface speeds up to 20 miles per hour. Pronounced and distinctive electrical anomalies have been obtained at every crevasse tested to date. Typical crevasse-detector recordings and details of the equipment and techniques used are presented. Some potential applications of the mutual-capacitance method in mineral prospecting and other fields are suggested.

THE PROBLEM

Crevasses are natural death-traps. Typically, a crevasse is a tension-crack formed in glacier ice by differential movement, from 1 foot to perhaps 100 feet in width. Crevasses are wedge-shaped, tapering to zero width at depths of from 50 to perhaps 200 feet below the surface (Schuster and Rigsby, 1954). They may be straight or sinuous, with lengths up to a mile. They may be partially filled with snow, icewater, vapor crystals, icicles, and shelves or floors of clear ice. In a zone of net snow accumulation, they usually are invisible from the surface of the glacier because the frequent storms which occur during their slow widening maintain a thin bridge of snow over the growing chasm (Schuster and Rigsby, 1954). The snow roof of a crevasse, seen from within, is frequently shaped like an unsymmetrical arch with a roof thickness of from one to perhaps 50 feet.

Many mountain climbers and polar explorers have lost their lives by falling into concealed crevasses. In Greenland, one such accident occurred as early as 1746 (Small, 1954). Several men, dog teams, sledges and motor vehicles have been lost since then during scientific expeditions and rescue missions on the Greenland icecap, particularly during World War II (Balchen, 1954). Similar accidents have occurred in the Antarctic, including two in 1955–56. Frequently, the men involved were experienced mountaineers or polar explorers (Small, 1954; Balchen, 1954). Even areas which have been tested by laborious probing with steel rods have been shown subsequently to include dangerous undiscovered crevasses.

Crevasse accidents are not always fatal, and rescues have often been effected with ropes (Schuster, 1954). Crevasse fields can be seen from aircraft under oblique illumination after a period of melting weather during which the snow

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bridges may sag slightly (Small, 1954). However, the need for an objective surface-operated means of detection which is operable in any weather and at night has long been obvious.

Serious efforts to find a suitable geophysical method were begun in 1953 and 1954 by the United States Army Transportation Corps' Arctic Group and the (Army) Engineer Research and Development Laboratories, with the placement of several research and development contracts. Several methods of geophysical exploration which have been tested in Greenland by various agencies are listed in this paper; however the only promising method discovered to date is the Surface Audio Frequency Electrical ("*SAFE*") method developed by Southwest Research Institute.

GEOPHYSICAL SOLUTIONS

The air within a crevasse constitutes a pronounced physical discontinuity in the glacier, particularly an acoustic and electrical one; the velocity of sound in compact ice may range from 7,000 to 12,000 ft/sec (for *P*-waves) and several modes of vibration are possible; the dielectric constant of glacier ice ranges from 30 to 75 at frequencies less than 1,000 cycles/sec (Dorsey, 1940). Also, the surfaces of a crevasse are favorably oriented to reflect wave energy uniquely since they are approximately at right-angles to the numerous sedimentary and metamorphic strata of snow, firn, and ice in the glacier. Furthermore, the depth to the air pocket is of the same order of magnitude as the width for all crevasses of interest. The detection problem appears to be amenable to attack by a variety of geophysical methods. The following methods have been tried:

(1) Measuring the intensity of the sound field at a constant distance of 40 feet ahead of a 30 to 60-cycle c.w. source as the system traversed a crevasse. Also other arrangements. Results: Expected interruption of energy paths by bridged crevasses was neither pronounced nor reliable; Coupling difficulties at the source and the pickup geophones; Cannot be used while in motion.

(2) Seismic-pulse refraction profiling. Results: Erratic time-vs-distance curves; First-arrivals rapidly variable in character and amplitude; No distinct crevasse effect, in profiles extending to 50 feet from source.

(3) Gravimeter profiles. Results: Small anomalies reported. Procedure slower than probing.

(4) Reflection of time-modulated microwave radio beam from under-side of crevasse bridge. Results reported to be too complex for ready interpretation; Serious absorption by surface moisture found.

(5) Profiling field strength from a 1.7 mc radio transmitter in traverses crossing crevasse. Results: No anomalies found.

(6) Measuring loading effect of glacier on radio antennas, operating at 12 to 156 mc, which were moved in a traverse at constant height above the surface, including work with balanced differential antenna arrays having three elements 4 to 8 feet apart, at heights of from 6 inches to 12 feet above the surface. Results: Clear and repeatable "crevasse anomalies" sometimes obtained with balanced

3-dipole system close to surface; Numerous equally large, repeatable false anomalies; Serious height or tilt effect; Probably disturbance by wet surface snow.

(7) Reflection of a 500 mc radio beam directed into the glacier at the polarizing angle, as source and receiver "look" into successive glacier areas during traverse. Results: Repeatable crevasse reflections apparently observed at several points 30 feet or more from certain crevasses, particularly with crossed polarizations: Numerous large, repeatable false anomalies elsewhere in the glacier; Probably disturbed by surface moisture.

THE "*SAFE*" METHOD

It occurred to the writer that an electric field of controlled "penetration depth" could be used to measure the effective dielectric constant of a selected volume of ice which should, in turn, indicate the presence of large voids above this "depth." A four-electrode system analogous to the Wenner-Gish-Rooney system of measuring effective conductivity (Jakosky, 1950) was selected for trial since the absolute properties of the medium are measurable with these systems almost independently of the electrode and circuit characteristics.

A fundamental difference lies in the fact that ice is essentially a nonconductor so that dielectric-displacement-currents rather than conduction-currents accompany any electric fields established in ice. The electrodes can interact with the ice and with each other only by means of electrostatic induction. The transfer function between the power and signal pairs of electrodes is a mutual capacitance. For this reason, alternating currents are logically used. Any appreciable stray capacitance between the power and signal circuits generally is harmful, as would be any cross-leakage admittance comparable to the electrode admittances. Hence, a "separated spread" like that shown in Figure 1 should be used so that the power and signal circuits can be physically well-separated.

Other basic design requirements readily are deduced: the electrodes should be large in area to secure low electrode reactances. Their spacings should be fixed and of the order of magnitude of the desired "working depth," that is, from 10 to 50 feet. The signal-indicating device V should be a high-input-impedance voltmeter so that the capacitive-decay time-constant of the signal circuit is longer than one half-cycle of the applied power. The power source S should be a constant-current source so that the signal e is proportional to the transfer reactance $X_t = e/I$, hence the effective dielectric constant of the ice k, despite variations in power-electrode reactance as the system is moved about in exploring the ice. Operating frequencies less than 1,000 cycles should be used to take advantage of the best contrast in dielectric constant between ice and crevasse air. The electrodes need not be in contact with the surface to be effective, but the air-gaps should be shorter than the widths of the electrodes for good coupling.

All of the aforementioned theoretical considerations have been verified by field tests in Greenland. Before these tests could be made, however, it was necessary to calculate the approximate magnitudes of the parameters involved. For this purpose, a rough preliminary theory was developed as follows:

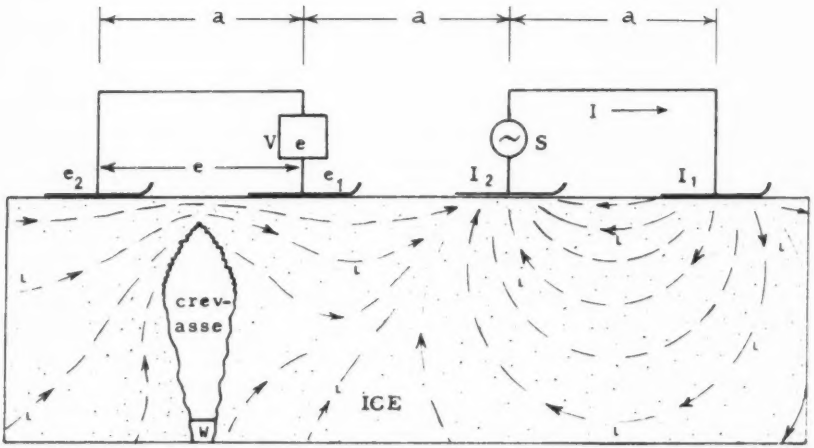


FIG. 1. Basic crevasse detector.

QUANTITATIVE DESIGN

Assume an infinitesimal volume of ice having a cross section A sq cm and a length dl (centimeters) parallel to the applied electric field. The capacitance between the ends of this volume, in electrostatic units and practical units respectively, is:

$$dC = Ak/dl \text{ e.s.u., and } dC = BAk/dl \text{ farads,} \tag{1}$$

where $B = 1.11 \times 10^{-12}$. The capacitive reactance is:

$$dX = 1/2\pi f \cdot dC = dl/2\pi fBAk = dV/dI \text{ ohms} \tag{2}$$

where dV is the r.m.s. potential difference between its ends (in volts) and dI is the total current[1] through it (in amperes). The current density $i = dI/A$ in this volume. Therefore, by substitution, the potential gradient in ice can be expressed in terms of the current density i, dielectric constant k and frequency f:

$$dV/dl = i/2\pi Bfk. \tag{3}$$

The potential is given[2] by LaPlaces' law, $\nabla^2 V = 0$, for which an appropriate solution, for radial flow of current from a single electrode, is:

$$V = -S/r + D \tag{4}$$

choosing $V = 0$ at $r = \infty$ gives $V = -S/r$. S can be evaluated by differentiating (4) and combining with (3):

$$dV/dr = S/r^2 = dV/dl = i/2\pi Bfk; \qquad S = ir^2/2\pi Bfk. \tag{5}$$

[1] For convenience, r.m.s. values of a.c. quantities are used throughout.

[2] Assuming approximately steady-state conditions, permissible because the wavelengths involved are very large compared to the region of interest.

Now, the current density i at a radial distance r from a (point) electrode at the ice surface depends only on the total electrode current I:

$$i = I/2\pi r^2. \tag{6}$$

Therefore, the potential at any point arising from a single current electrode is, according to (4), (5) and (6):

$$V = -ir/2\pi Bfk = -I/4\pi^2 Bfkr. \tag{7}$$

The potentials from two electrodes of opposite sign can be added algebraically, since LaPlaces' equation is linear and homogeneous in V. For the situation shown in Figure 1, the potential at signal electrode e_1 is:

$$V_1 = \frac{I}{4\pi^2 Bfk}\left(\frac{1}{a} - \frac{1}{2a}\right)$$

and that at electrode e_2 is:

$$V_2 = \frac{I}{4\pi^2 Bfk}\left(\frac{1}{a} - \frac{1}{2a}\right)$$

the potential difference measured is:

$$e = (V_1 - V_2) = I/12\pi^2 Bfka \text{ volts} \tag{8}$$

which depends only upon the effective dielectric constant k for the ice in the vicinity of the system, providing the supply current I (in amperes) is kept constant. Equation (7) gives the potential required at each current electrode, considered to be equivalent to a hemisphere of radius r buried flush with the surface, to produce an electrode current I. The capacitive reactance per electrode is:

$$X_e = V/I = 1/4\pi^2 Bfkr \text{ ohms}. \tag{9}$$

Assuming the following practical values of parameters: $e = 1$ volt, $k = 30$, $f = 400$ cps, $r = 50$ cm, $a = 500$ cm, the remaining design parameters are given by formulas (7), (8) and (9): Current $I = 0.8$ milliampere; Applied Voltage $E = 60$ volts; Electrode Reactance $X_e = 12{,}500$ ohms.

In the field tests performed, it was found that values of current and applied voltage several times the predicted values were required to obtain signals of one volt. The formulas derived, therefore, must be considered nothing more than approximations.

ANOMALIES

To date, an attempt has not been made to calculate the effect of a crevasse on the electrical indications of the system. By analogy to published resistivity traverses over a buried igneous dike, it was assumed, at first, that over a crevasse, an anomalous increase of the signal by an amount of the same order of magnitude as the normal signal e could be expected.

To provide a better estimate, a model test was performed. "Crevasses" were drilled below the surface of a 150-pound block of ice, which was explored by means of a miniature set of spring-loaded electrode plates as shown in Figure 2. The power electrodes were energized by an audio oscillator through an isolating transformer having only 4 mmfd of stray capacitance between the floating secondary and the (grounded) primary. As a signal indicator, a (grounded) vacuum-tube voltmeter was used. Shielded cable had to be used from the signal

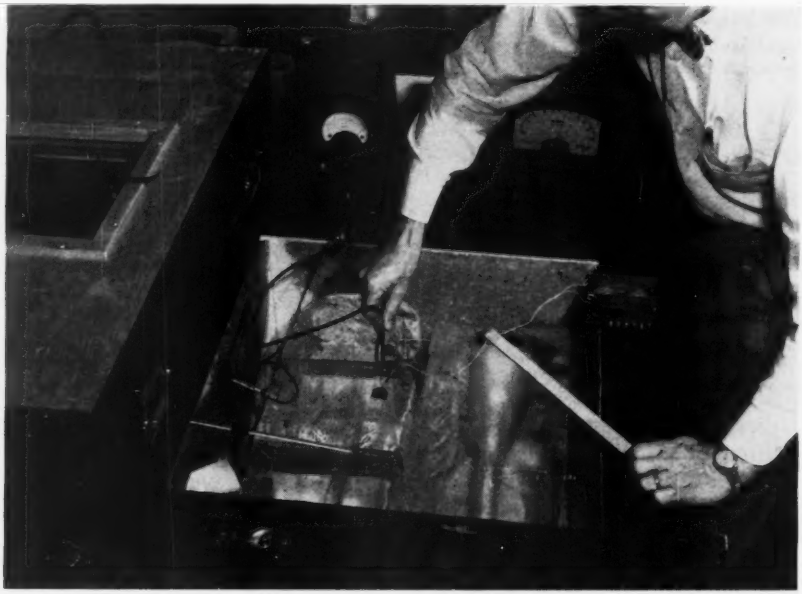


FIG. 2. Model test of surface-electrode system.

electrodes to this voltmeter, but the factor by which its shunt capacitance reduced the signal readings was calculated and an appropriate correction was made.

This experiment produced double-peaked "crevasse anomalies" of the size expected over the "shallow crevasse." That is, the peak readings e' of signal voltage were double the average normal background signal $\bar{e}$.

FIRST PRACTICAL RESULTS

Following this encouraging laboratory result, full-scale tests were carried out under the auspices of the Engineer Research and Development Laboratories, supported in the field by the First Army Engineers Arctic Task Force and performed during July 1955 on the Greenland icecap above Thule at an elevation of 3,400 feet. In Figure 3 the rapid development of the method early in this period

is illustrated diagrammatically. Sheet metal sleds 4 feet square were used as electrodes throughout.

The stationary test arrangement shown in Figure 3a was tried on wet snow (air temperature 38 degrees F). The following observations were made at 400 cycles/sec:

1—The transfer signals e are steady, repeatable, and much larger than extraneous or system noise. At an input voltage $E = 200$ volts; $I = 1.5$ milliamperes and signal $e = 0.5$ volt for an electrode spacing, $a = 35$ feet.

2—Electrode impedances are 60,000 ohms each, equivalent to a self-capacitance of 0.007 mfd. Therefore, the signal indicator need not have an input impedance much greater than 1 megohm.

3—Normal electrode motion over smooth snow causes current and signal fluctuations of at least ± 10 percent. This can be reduced to ± 1 percent by weighting each sled (with snow) to 10 lb/square foot. A current-regulating resistor $R = 1$ megohm is less effective.

4—The electrodes are effective at heights of several feet. The interconnecting wires also act as inefficient shunting electrodes, especially when in firm contact with the snow. These wires should be supported above the surface.

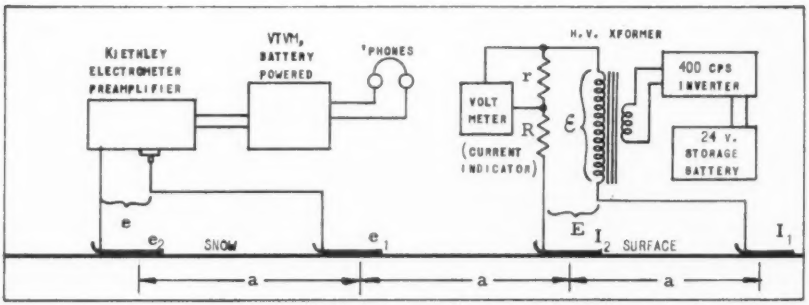
The mobile test system of Figure 3b incorporated these recommendations. It was used to observe background fluctuations and indications from an actual crevasse which was crossed at points believed to be safe. It produced crevasse readings approximately double the normal average. The background fluctuations were approximately half the crevasse anomaly.

The system of Figure 3c employed a "weasel" vehicle as one signal electrode. The other was towed ahead as a warning electrode. Automatic signal recording was incorporated to permit detailed study of the resulting profiles. Portions of the very first profiles recorded with the system are shown in Figure 4. These profiles illustrate the repeatability obtained. The double-peaked anomaly was produced by crossing a crevasse which was approximately 9 feet wide and 20 feet deep (to water level) at a point where it had been dozed full of packed snow to provide a safe crossing for vehicles. Apparently the snow filling was incomplete, or was of lower dielectric constant than the surrounding ice as an anomaly was produced. The first peak occurred approximately midway between the first and second electrodes, and the second peak midway between the third and fourth electrodes. A distinct crevasse warning had therefore been shown when the weasel was still 10 feet from the edge of the crevasse.

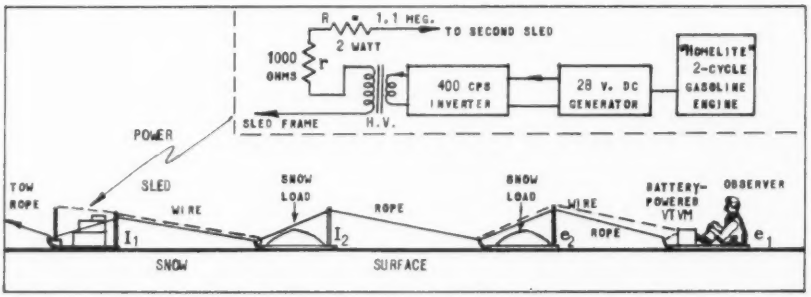
The severe decrease in signal shown in Figure 4b subsequently was found to be a unique and positive indicator of electrical failures in the system.

FIELD EXPLORATION

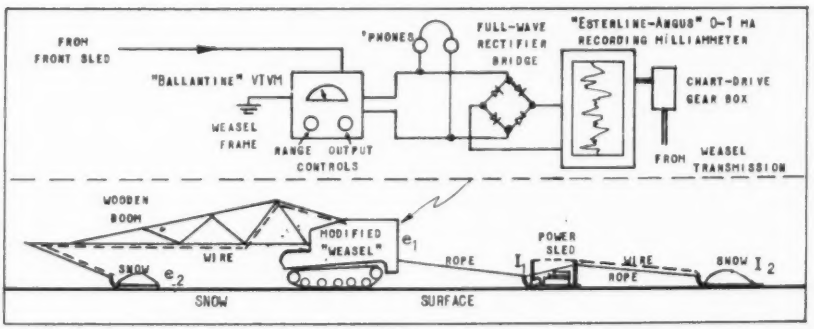
In order to obtain data on the behavior of the system in various areas of the icecap, over 250 miles of traverses were run at speeds from 2 to 20 miles per hour on the established trails. The arrangement used was like that shown in Figure 3c except that the clumsy suspended boom was removed and all three sleds were



First Full-Scale Test Setup, July 6, 1955.

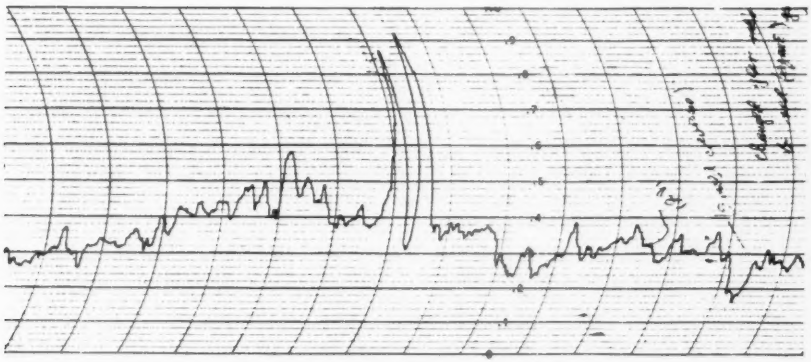


First Mobile System, with Human Observer, July 10.

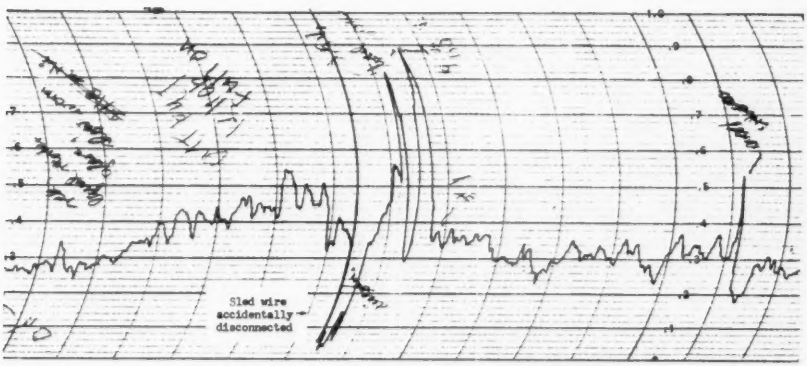


First Automatic, Recording System, with "Weasel" Electrode, July 14.

FIG. 3. Early evolution of four-electrode system.



FIRST CREVASSE ANOMALY RECORDING.



REPEAT RECORDING.

FIG. 4. First four-electrode signal recordings.

dragged behind the weasel. Electrode spacings of 20 feet and a frequency of 400 cps were employed. Figure 5 illustrates several crevasse anomalies (occurring at crevasses 4 to 10 feet wide, filled with snow) and types of background profile which were encountered at various distances (shown in miles) from the edge of the ice sheet (and therefore at various elevations). The horizontal scale in each profile is 480 ft per division except as noted in Figure 5d. The edgepen signals at the bottom edge of each profile indicate the passage of mile or quarter-mile markers, or crevasse and crack markers placed beside the icecap trail. Repeat profiling has shown that most of the details in the profiles are real and repeatable.

It can be seen that the background becomes relatively smooth far inland where the near-surface material is uniform and of simple structure. In the abla-

tion zone near the coast, however, the effective dielectric constant "seen" by the device is highly variable, probably the result of the complex ice structure. Some background features have been correlated with known groups of cracks (each generally less than a foot wide) or areas filled with "mushy snow holes." All the known crevasses crossed were clearly indicated, but these indications were sometimes difficult to distinguish from "false alarms" as shown in Figure 5a. This fact indicates that continuous visible recording of the signal probably will continue to be necessary for reliable interpretation, at least until much more experience has been obtained with this method.

It is probable that the particular system used to produce Figure 5 was not the optimum for the purpose. Other arrangements have since been found which appear to produce a better distinction between crevasses and other kinds of discontinuities in the ice.

SYSTEMATIC TESTS

During the remainder of the 1955 summer field season in Greenland, several hundred profiles were recorded on traverses across a few selected crevasses. Data were obtained on the effects of several system parameters. Numerous combinations of conditions remain untested at this time, and several of the parameters appear to be interdependent in their effect. The results were evaluated in terms of two numbers:

(a) The "Alarm Factor" f: crevasse-anomaly peak voltage divided by average normal signal background voltage.

(b) The "Figure of Merit" F: crevasse-anomaly peak-to-trough amplitude divided by the average amplitude of spurious signal variations of similar "wavelength" or character.

Since the background variations were found to vary tremendously in amplitude and character from area to area on the icecap, the "Figure of Merit" was necessary to indicate the distinctness of a crevasse anomaly under any background conditions. The results of these tests can be summarized as follows:

(1) Four electrodes are probably necessary. Profiles run with two-electrode and three-electrode circuits did not exhibit any crevasse anomalies comparable to the background variations. This result was foreseen from theory.

(2) Four-electrode systems are effective in the following arrangements:

(a) In a line moving along its axis

(b) In a line moving broadside

(c) In a square (*H*-pattern) moving perpendicular to the wires connecting the sleds of each pair.

In these tests, the crevasse was crossed approximately at right angles. When in accurate alignment with the crevasse, (b) gives an anomaly twice as large as (a) for short electrode spacings.

(3) Electrode spacings of from 7 feet to 180 feet have been used successfully. Using the axial-line arrangement, the anomaly is double-peaked with a low center (like Figure 4) at spacings greater than 30 feet. As in Figure 5, the peaks become

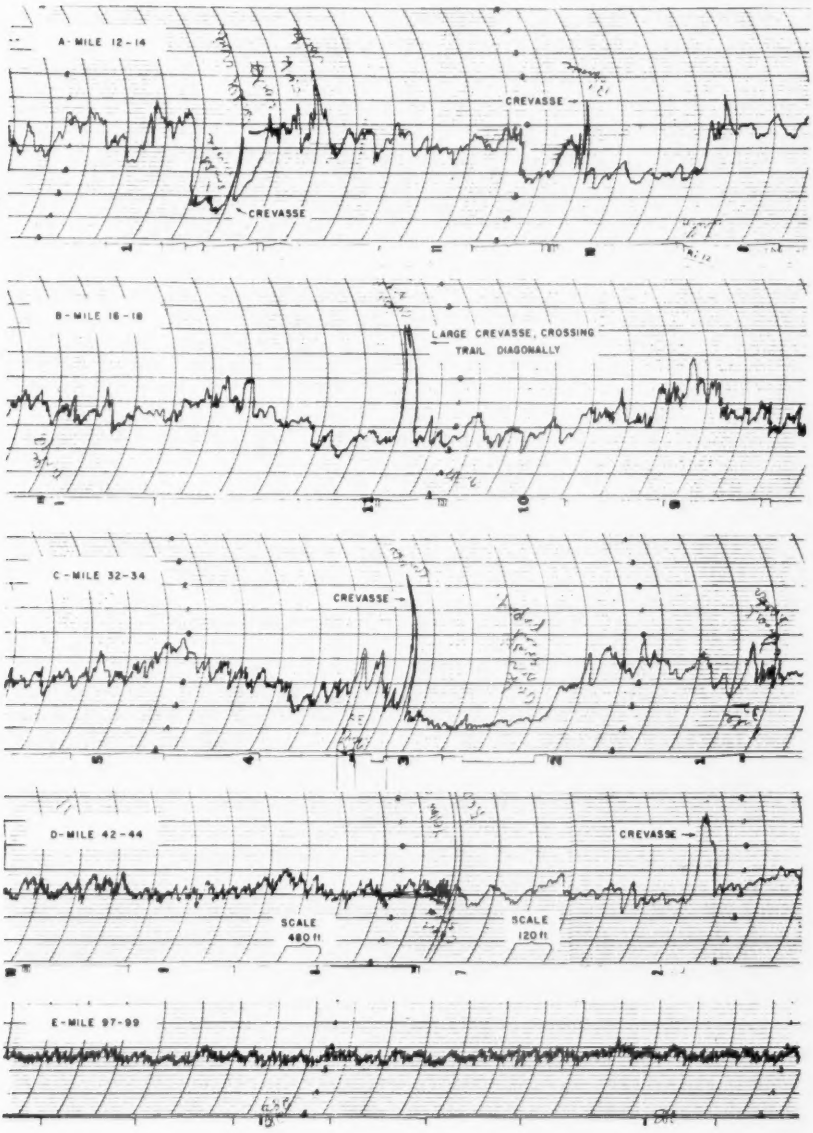


FIG. 5. Background character vs distance from the coast.

fused at smaller spacings. The shortest spread giving good discrimination (F = 3 to 6) between crevasses and "background irregularities" has unlike spacings of 20, 40, and 20 feet. Permutations of electrode order do not have any effect so long as a "separated spread," like that in Figure 1, is used.

(4) The best operating frequencies (F and f greater than 2) lie below 400 cycles/sec. Profiles over a crevasse at two places at various frequencies are shown in Figure 6. The optimum frequency appears to depend on the electrode spacing, snow dryness, and crevasse size. On wet snow, 200 cps was best (F = f = 4). On dry snow, 60 cycles or lower sometimes gave $F \approx f > 12$. High audio frequencies always gave F = f = 1.5.

(5) The best crevasse anomalies are obtained at subfreezing temperatures. However, frozen, dry snow also produces frictional-electric noise at the signal sleds amounting to as much as 0.2 volt rms at 20 miles per hour for the signal circuit of Figure 3c (using a meter with a ½ megohm internal input shunt). This noise appears in the "background" of Figures 5e and 6.

(6) A large void in the snow can be detected at lateral distances up to 20 feet from the path of the electrode line.

In Figure 7 is shown the interior of the crevasse used in most of the systematic tests. This crevasse extended below a depth of 50 feet and was typical in all respects of several which were explored. It will be described elsewhere in greater detail (Cook, 1956).

MISCELLANEOUS RESULTS

Many additional useful observations were made. On one occasion, two "Atwell" buildings (made of wood and canvas, 16′×24′×8′ in dimensions) buried under 2 feet of snow were located readily with the crevasse detector. False high signal readings were obtained during turns and when the sleds coasted ahead of their tow-ropes on steep slopes, because of the resulting alteration of electrode spacing. Therefore, it was customary to disconnect the signal during turns (Figure 6). Destructive electrical leakage along the tow-rope between the power and signal sleds occurred during snowstorms from wetting. This caused a slow but pronounced rise of the apparent background signal. The spurious current path finally was broken by inserting a glazed porcelain insulator which was frequently wiped dry during wet snowstorms.

Several experiments were run with circuit isolation by means of magnetic and electron-stream coupling devices. Good crevasse anomalies were obtained with the power electrodes energized from the weasel through a special transformer built as shown in Figure 8a. This transformer had a capacitance between primary and secondary of 20 mmfd. Attempts to use a conventional transformer with 600 mmfd between windings failed; crevasse anomalies could not be obtained. A cathode-follower circuit, essentially like that shown in Figure 8b, was successfully used to isolate the weasel (and observer) from a remote pair of signal electrodes. However, in cold weather, the 10-megohm grid-reference resistors had to be shunted by 1 megohm each to overcome an effect believed to be tube saturation

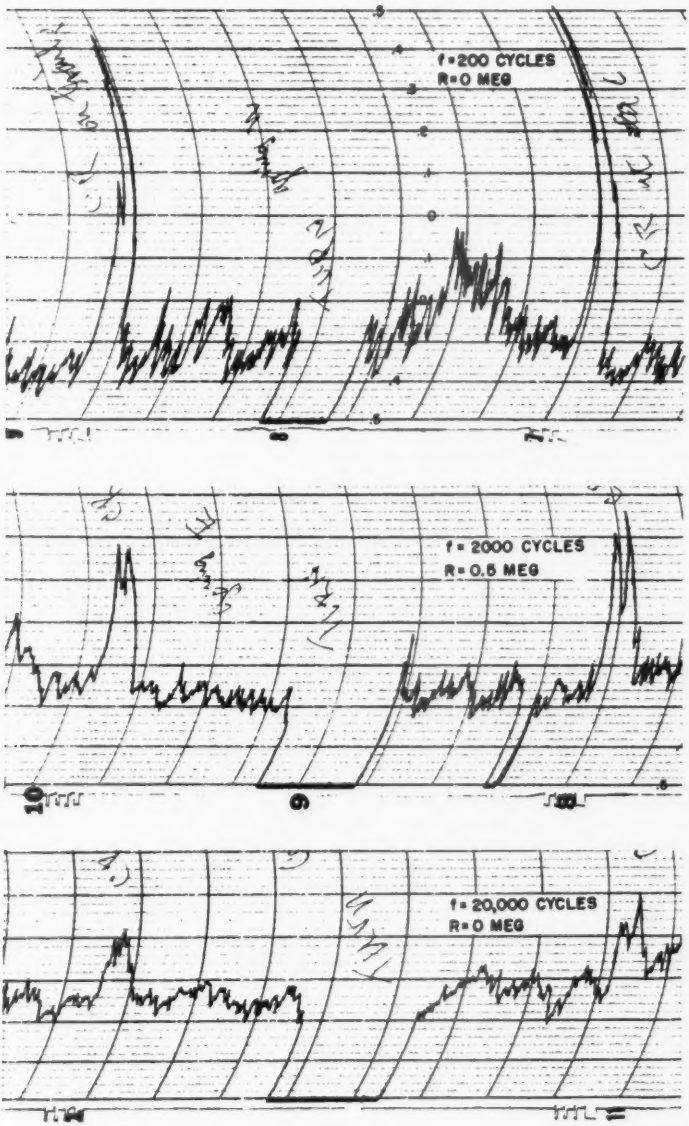


FIG. 6. Profiles at various frequencies, August 11.

by friction noise. Circuit isolation devices permit consolidation of all the energy sources and instruments within the shelter of the weasel.

The small portable system shown in Figure 9 also was developed and tested with reasonably good results. The observer and his metal-covered skis served as one signal electrode. Aural indication with headphones was used. The battery-powered amplifier, worn inside the clothing, included an adjustable threshold circuit consisting of a biased diode. It was adjusted so that normal background signals were just below the threshold. Crevasse signals exceeding the threshold

FIG. 7. View inside a crevasse in North Greenland. Crevasse is ten feet wide and personnel are exploring an ice shelf twenty feet below the surface.

produced a loud warning note. The power source was a small 400-cycle, 6-watt rotary inverter and a step-up transformer energized by a small lead-acid storage battery capable of operating them for a period of 2 hours.

Two defects in this device were noted: (a) background fluctuation required continuous readjustment of the threshold which might better be done by a slow automatic-gain-control circuit; (b) the system did not give any warning to the operator until he had passed over the crevasse. Attempts to push one electrode ahead with a pole were abortive because of maneuvering difficulties and the shortness of the electrode spacing available by this method.

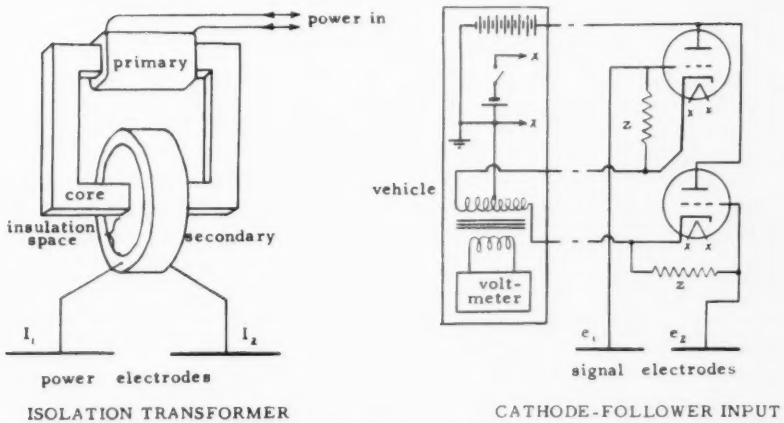


FIG. 8. Two circuit-isolation methods. a. Isolation transformer. b. Cathode-follower input.

PRESENT STATUS

The work herein reported is being followed up by the Engineer Research and Development Laboratories, with an extensive program of research, construction, and testing of practical crevasse-detector units. Some of this work is now in progress at Southwest Research Institute.

A device similar to that shown in Figure 3c, except that a recorder was not used, was built by Navy personnel according to instructions provided by Engineer Research and Development Laboratories and was tested in the Antarctic during December 1955 and January 1956 (Dempewolff, 1956). It is reported that all the known crevasses in an area of shelf ice were indicated, and that some additional ones were located. However, the reported character of the anomaly is puzzling; it consists of a sharp *decrease* in signal beginning when the first electrode

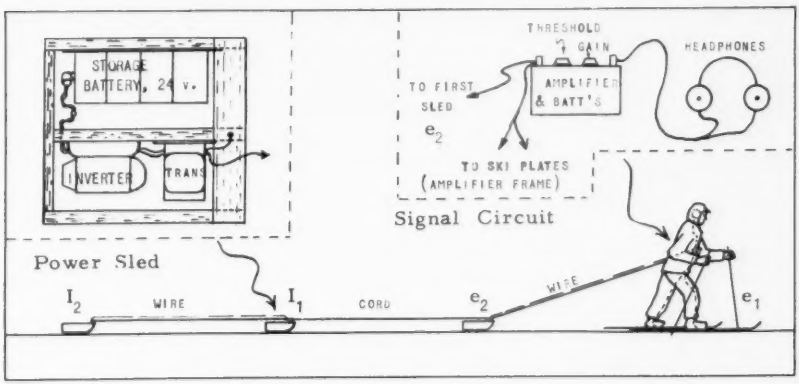


FIG. 9. One-man (portable) four-electrode system.

has reached the crevasse. This apparent inversion of the crevasse effect measured on the model and in Greenland has not yet been explained. It is surmised that it may involve some effect peculiar to wet shelf ice, and that further inland in Antarctica, a transition to the more familiar type of anomaly may take place.

OTHER APPLICATIONS

It is obvious that four-electrode mutual-capacitance measurements can be applied to a variety of problems involving concealed discontinuities within a dielectric body. One use of particular interest to exploration geophysicists has been suggested: the determination of depth and configuration of the water table or bedrock beneath desert sands. Likewise, mineralized zones of good conductivity beneath dry rock or sand might be detected by means of this technique, where the conductivity of the surface material is too low to permit the use of conduction-electrode methods, providing electromagnetic methods are unsuitable.

Another suggested use is in the location of sinkholes beneath airport runways, the conductivity of which is too low to permit the use of resistivity methods. In concrete runways, fortunately, reinforcing iron is frequently not used. A related use is in the location of dry limestone caves.

ACKNOWLEDGMENTS

The author is indebted to the Engineer Research and Development Laboratories and the Project Engineer, Mr. Lynn A. Smitherman, for their support and harmonious cooperation in this work; to Mr. Joseph Wormser of Southwest Research Institute for his valuable assistance and original contributions during the Greenland field work, in particular, the "broadside" electrode arrangement and the isolation-method depicted in Figure 8b; and to the Department of Defense for permission to publish this condensation of the Final Report on Contract DA-44-009-ENG-2315.

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GEOPHYSICS, VOL. XXI, NO. 4 (OCTOBER, 1956), PP. 1071-1086, 6 FIGS.

RESISTIVITY OF SANDSTONES AS RELATED TO THE GEOMETRY OF THEIR INTERSTITIAL WATER*

F. M. PERKINS, JR.,† J. S. OSOBA,† AND K. H. RIBE†

ABSTRACT

It is extremely desirable in the interpretation of resistivity measurements made on porous media containing saline water and hydrocarbons to have at hand a better knowledge of the geometry of the conducting salt water.

One geometric characteristic is the tortuosity of the aqueous phase. A method was devised several years ago for the measurement of the tortuosity of completely brine-saturated sands by the measurement of transit time of ions migrating through the aqueous phase under a potential gradient. This method has been improved and extended to the investigation of the tortuosity of sands containing both brine and oil.

Results obtained to date on a group of sandstone samples containing water and oil indicate that there is a relation between the tortuosity of the aqueous phase, the brine content of the sand, the resistivity of the brine, and the resistivity of the gross sample. These results were used to relate the saturation exponent, n, which is customarily used in the interpretation of the electric log, to the tortuosity and apparent cross-sectional area of the electrolyte through which electric current flows.

INTRODUCTION

Quantitative interpretation of the electric log to yield information on the fluid content of a permeable stratum requires a knowledge of particular resistivity characteristics of the stratum. One such characteristic is usually expressed as the *resistivity factor* (Sundberg, 1932; Archie, 1942), which is defined as the ratio of the resistivity of a porous material completely saturated with an electrolyte to the resistivity of the electrolyte itself. Another characteristic, employed in the estimation of hydrocarbon saturations from resistivity data, is ordinarily expressed as the *saturation exponent* (Archie, 1942), and is defined as the exponent which appears in the equation relating water saturation to the resistivity of the stratum containing both water and hydrocarbon and to the resistivity of the rock containing water alone.

It is apparent that such characteristics should be capable of expression in terms of geometric significance, since, fundamentally, they are determined by the geometry of the pore spaces within the permeable rock. Reduction to geometric expression has the distinct advantage of facilitating understanding and appreciation of the factors which influence the resistivity behavior of earth strata.

As the result of an investigation of the geometric significance of the resistivity factor, Winsauer and co-workers (Winsauer et al., 1951) showed that the resistivity factor could be expressed by the relation

$$F = \frac{\tau}{\psi} \tag{1}$$

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where

F is the resistivity factor,

τ is the tortuosity, defined as the ratio of the tortuous length of the pore channels in a brine-saturated rock traversed by an electric current flowing between two parallel planes within the rock to the distance between the planes,

ψ is the ratio of the apparent cross-sectional area of the conducting electrolyte to the total cross-sectional area of rock and contained electrolyte.

From a consideration of the physical significance of τ and ψ, it was also shown that, in the absence of pore channels filled with electrolyte but ineffective in conducting current, the resistivity factor should be related to the tortuosity and the porosity of the rock, p, by

$$F = \frac{\tau^2}{p} . \tag{2}$$

As part of the investigation, a procedure was devised for measurement of the tortuosity by measurement of the transit time of ions moving through the brine-saturated rock under a potential gradient. The experimental results indicated that the resistivity factor was related to the tortuosity and porosity not by the above relation, but rather by the empirical relation

$$F = \frac{\tau^{1.67}}{p} . \tag{3}$$

Although it was realized at the time that a systematic error in the determination of the tortuosity could account for failure of the experimental results to verify Equation (2), no source of systematic error was evident. Subsequently, however, it has been pointed out by Overbeek (1953) that the particular electrochemical system used in the determination of the tortuosity could give rise to an error which would affect the measurements. A slightly different electrochemical system and procedure were suggested by Overbeek to minimize errors from this source.

The investigation described in the following sections was undertaken with several objectives in mind. First, in the light of Overbeek's observation, it was desirable to redetermine the tortuosities of sands completely saturated with brine and to reinvestigate the relationship between the resistivity factor and the tortuosity and porosity. A second objective was to extend the measurement of tortuosities to sands containing both brine and hydrocarbons. The third objective was to investigate the significance of the saturation exponent in terms of the geometry of the portion of the pore space filled with interstitial water.

PLAN OF INVESTIGATION

In order to achieve these three objectives, it was necessary that attention be given first to reinvestigation of sandstones completely saturated with brine, for

attainment of the other objectives was dependent upon the success of work conducted on brine-saturated sands. Accordingly, careful consideration was given to minimizing experimental errors of the type which Overbeek had suggested as entering into the previous work.

In the work which Winsauer and his co-workers conducted, the sandstone sample was saturated with a sodium nitrate solution, one end of the cylindrical sample was placed in contact with a solution of sodium chloride, a constant potential was applied across the system, and the time required for the chloride ion to migrate through the sample was measured. The transit time required for the chloride ion to migrate through a solution in a straight capillary of known length under a known potential gradient was measured in auxiliary experiments, and the tortuosity of the sandstone sample was computed by use of the relation

$$\tau = \left(\frac{t'}{t}\right)^{1/2} \tag{4}$$

where

t' is the time required for transit of unit length of brine-saturated sample under unit potential gradient,

t is the time required for transit of unit length of brine-filled straight capillary under unit potential gradient.

In reviewing this work, Overbeek pointed out that the mobility of the chloride ion is greater than that of the nitrate ion so that it overtakes the nitrate ion in the course of its migration. This results in the building up of a high concentration of salts in the neighborhood of the advancing chloride front. This, in turn, results in local variations of density of the solutions, which can, under proper circumstances, lead to disturbing gravitational effects. For example, as visualized by Overbeek, one effect of this chain of circumstances should be the introduction of an error into the determination of the transit time of the chloride ion measured in straight capillary tubes. This error should be such that the apparent transit time is less than the true value; the tortuosities computed from Equation (4) by use of the apparent value of t should consequently be too large.

To obviate error due to this source, Overbeek suggested that the electrochemical system be changed so that the invading anion have lower mobility than the resident anion. This condition can be fulfilled by use of a sodium chloride solution as the resident electrolyte and of a sodium acetate solution in lieu of the sodium chloride solution used by Winsauer.

The plan of attack in reinvestigating sandstones completely saturated with brine was thus to repeat the work of Winsauer, with substitution of electrolytes as suggested by Overbeek. To investigate the tortuosities of the aqueous phase of sandstones containing both brine and hydrocarbons, it was only necessary to change slightly the experimental techniques for investigating the samples completely saturated with brine.

EXPERIMENTAL PROCEDURE

The porosity, the resistivity factor, and the tortuosity were determined on a number of consolidated and unconsolidated sands which were completely saturated with water. In addition to the measurements at complete water saturation, the tortuosity, the resistivity of the sample, the resistivity of the contained electrolyte, and the electrolyte saturation were measured when the sample contained both water and hydrocarbons. These measurements are described in the following sections.

Sample Preparation and Determination of Porosity and Water Saturation

Indurated sandstone cores were selected to provide samples from different geologic ages and geographic locations. Small cylindrical plugs approximately 1″ in diameter and 1″ in length were cut from the cores.

The unconsolidated sand samples were prepared by filling lucite tubes approximately 1″ in diameter and 1″ in length with 70 to 200 mesh Ottawa sand and cementing a fine-weave, nylon cloth over the ends.

Sample preparation for tortuosity and resistivity determinations on cores containing water and oil usually necessitated the use of a non-wetting material that would not be displaced spontaneously when the core was in contact with water. For this purpose, a low melting point paraffin was used as the oil phase. Various water saturations were obtained by flushing the cores in a conventional flooding apparatus. After a sample had been flooded with molten paraffin to the desired saturation, it was allowed to equilibrate in the molten state before cooling to room temperature. For tortuosity determinations at residual oil saturation, kerosene was generally used for the oil phase, since imbibition forces are not active at this saturation. The water saturation was determined either by material balance of injected and produced liquids or by gravimetric methods.

Determination of Resistivity Factor and Resistivity Ratio

The resistivity factor of each core sample was determined when completely saturated with a 0.50N sodium chloride solution.

A quantity which was found to be useful in describing the resistivity behavior of core samples containing both water and oil is the ***resistivity ratio***, F_s, which is defined as the ratio of the resistivity of the core sample containing saturation S of electrolyte to the resistivity of the electrolyte. In the resistivity ratio measurements a 0.50N sodium chloride solution was used as the electrolyte.

Tortuosity Determinations

The equipment and procedure for the tortuosity measurement were similar to those used by Winsauer and co-workers. The important differences will be discussed in the following paragraphs.

In the present work, a 0.50N sodium chloride solution was used as the resident solution. The concentration of sodium acetate solution used to furnish a sharp

boundary of "invading" acetate ions was chosen, in accordance with Kohlrausch's principle (Kohlrausch, 1897) to be 0.37N.

To determine the tortuosity of a particular sample the core was either saturated completely with 0.50N sodium chloride solution or was filled with a 0.50N sodium chloride solution and a hydrocarbon. The sample was then placed into the Hassler type core holder, and the apparatus was assembled as is shown in Figure 1. In the tortuosity determination, current was passed between the two platinum electrodes shown in Figure 1. The current was furnished by an electronically regulated source constructed so that a constant current of any desired value was maintained throughout the run regardless of resistance changes anywhere in the circuit. During the run, periodic measurements were recorded of the time of current flow and of the potential of the silver-silver chloride electrode, measured with respect to a calomel reference half-cell. The appearance of the acetate-chloride ion boundary at the lower face of the sample was indicated by a sudden increase in the detecting electrode potential, which reflected a decrease in chloride ion concentration.

In order to eliminate the effects of sample length and of the potential gradient,

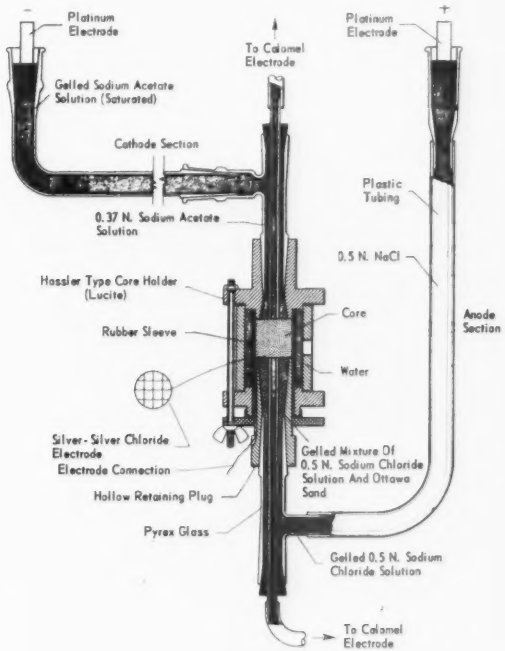

FIG. 1. Apparatus for measuring resistivity and tortuosity of samples.

the actual time for a boundary to move through a sample was converted to a "unit time," which is the time which would apply if the length of the sample were one centimeter and the potential difference across the sample were one volt when the run was initiated. The potential between the silver-silver chloride electrode and the calomel half-cell was then plotted against the unit time in the manner exemplified in Figure 2. As demonstrated in this figure, a sudden change in the slope of the curve indicates the appearance of the acetate ion. This was taken as the correct unit time.

Considerable difficulty was experienced in getting good break-through curves for samples containing an appreciable amount of argillaceous material. A critical analysis of the results of runs on several samples pointed to the ionic double

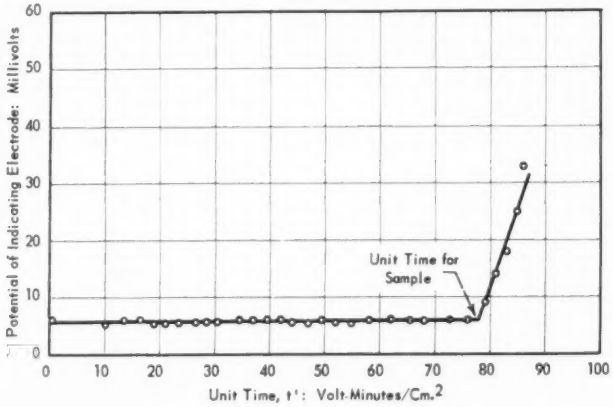

FIG. 2. Typical plot for determining the time for the ionic boundary to traverse a sample.

layer as the cause of the anomalous results. It was found that this effect was aggravated by the presence of hydrocarbons. For this reason, only a few samples containing both water and oil could be run, whereas most of the samples gave good break-through curves when they were completely saturated with water.

To obtain the unit time of the chloride ions when migrating through a sample of unit tortuosity under the conditions used in the tortuosity measurements, measurements on straight capillary channels were made by use of the procedure previously described. The results of three runs on the same bundle of straight capillaries are tabulated below.

Run Number	*Current Amperes*	*Time for Boundary to Traverse Sample Minutes*	*Unit Time Volt Min/cm²*
1	0.030	84.0	29.0
2	0.050	50.1	30.1
3	0.020	128.4	31.4
		Average	30.2

Since the rate of boundary movement during Run 2 was more than twofold that in Run 3 with no discernible change in the unit time, it may be concluded that the boundary movement was not affected by diffusion. The small variations which occurred are thought to be due to random experimental error.

The chloride ion mobility which may be calculated from the above data is in agreement with values reported in the literature.

RESULTS

Table I gives sample descriptions and properties, results of measurements of resistivity factor, resistivity ratio, and tortuosity for each of the samples investigated.

Tortuosity measurements were made at complete water saturation on several samples of unconsolidated sand, on two outcrop samples of indurated sandstone, and on fifteen sandstone samples taken from cores of wells. The latter represented a wide variety of textural types and a number of geologic ages.

Relation of Resistivity Factor to Tortuosity and Porosity

Data obtained on sands completely saturated with brine permitted investigation of the relationship between the resistivity factor and the tortuosity and porosity. Figure 3 is a plot, on logarithmic coordinates, of the product of the resistivity factor and the porosity against the tortuosity.

As shown in Figure 3, Equation (2) gave an excellent representation of the data. It may thus be concluded that Equation (2) is valid for the sandstones in-

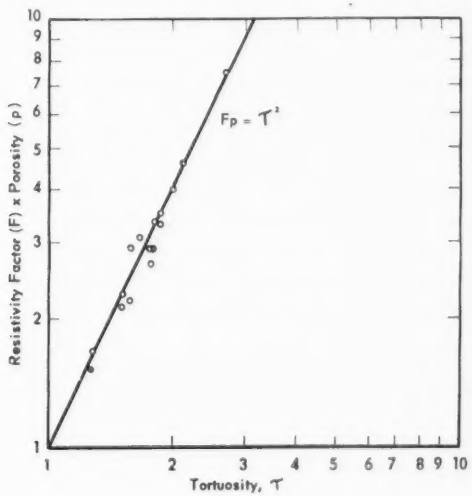

FIG. 3. Relation of porosity times resistivity factor to the tortuosity.

TABLE I

DESCRIPTION AND ELECTRICAL AND PHYSICAL PROPERTIES OF SAMPLES

Sample No.	Strata	Location	Depth Feet	Porosity Per Cent	Water Saturation Per Cent	Resistivity Factor F	Resistivity Ratio F_s	ϕ or ϕ_s	Tortuosity τ or τ_s
1	Gibson (3rd Deese), Penna.	Elmore, Okla.	6,400	17.4	100	19.4	19.4	0.094	1.82
2	Bradford, Dev.	Penna.		14.7	100	51.0	51.0	0.054	2.74
4A	Weber, Penna.	Rangely, Colo.	6,100	17.6	100	16.6	16.6	0.110	1.83
5	Woodbine, U. Cret.	Hawkins, Texas	4,600	26.3	100	8.6	8.6	0.177	1.52
10-B	Tensleep, Penna.	Elk Basin, Wyo.	5,600	13.9	100	33.0	33.0	0.064	2.13
12	Cromwell, Penna.	Oklahoma	1,700	18.8	100	17.7	17.7	0.106	1.88
23-A	Frio, Olig.	Matagorda, Texas		24.8	100	10.8	10.8	0.165	1.78
32	Frio, Olig.	Fishers Reef, Tex.	9,000	26.7	100	10.9	10.9	0.146	1.59
35	Yegua, Eocene	Liberty Co., Tex.	7,700	30.7	100	6.9	6.9	0.219	1.51
36-A	Frio, Olig.	Kelsey, Texas	6,000	25.1	100	11.6	11.6	0.155	1.80
40	Berea, Miss.	Amherst, Ohio	outcrop	18.4	100	19.0	19.0	0.099	1.88
K-3	Woodbine, U. Cret.	Tyler, Texas	3,600	28.8	100	7.7	7.7	0.206	1.58
H-2	Wilcox Eo.	Victoria Co., Texas	8,100	16.7	100	23.9	23.9	0.085	2.02
B-3	Berea, Miss.	Amherst, Ohio	outcrop	18.8	100	17.7	17.7	0.106	1.88
B-2S4	Frio, Olig.	Kleberg Co., Texas	6,900	25.1	100	12.2	12.2	0.137	1.67
K-2	Woodbine, U. Cret.	Tyler, Texas	3,600	28.4	100	8.5	8.5	0.189	1.60
K-2	"	"	"	"	80.5	--	12.2	0.119	1.70
K-2	"	"	"	"	74.0	--	13.1	0.126	1.65
K-2	"	"	"	"	53.0	--	20.8	0.072	1.93
K-2	"	"	"	"	30.0	--	68.7	0.037	2.57
W-3	Woodbine, U. Cret.	Tyler, Texas	3,600	28.4	100	8.1	8.1	0.188	1.52
W-3	"	"	"	"	80	--	13.9	0.129	1.79
W-3	"	"	"	"	80	--	13.3	0.132	1.76
W-3	"	"	"	"	43.5	--	50.1	0.048	2.40
W-3	"	"	"	"	29.9	--	135.5	0.024	1.26
U-1	Artificially prepared unconsolidated sand	--	---	36.7	100	4.5	4.5	0.284	1.28
U-2	Artificially prepared unconsolidated sand	--	---	37.5	100	4.0	4.0	0.311	1.26
U-2	" " " "	---	---	"	77.5	--	7.6	0.213	1.62
U-2	" " " "	--	--	"	25.3	--	61.1	0.042	2.56
U-3	Artificially prepared unconsolidated sand	--	---	37.5	100	5.4	5.4	0.252	1.36
U-3	" " " "	---	--	"	79.0	--	8.6	0.181	1.56
U-3	" " " "	--	--	"	58.0	--	14.7	0.118	1.73
U-3	" " " "	-	--	"	33.4	--	65.5	0.043	2.83

vestigated, and that it likely applies to sandstones in general. This is in accord with the views of Nielsen (1953) and Cornell and Katz (1953)

The agreement of the experimental data with Equation (2) suggests that there was little or no volume of electrolyte within the pore space which failed to contribute to flow of the electric current.

Relation of Tortuosity to Porosity, Water Saturation, and Resistivity Ratio

Consideration of the geometry of the electrolyte-filled portion of the pore

space of a porous material which contains both hydrocarbons and electrolyte leads to an expression similar to Equation (1) that relates the resistivity ratio, F_s, to τ_s and ψ_s at water saturation S.

$$F_s = \frac{\tau_s}{\psi_s}. \tag{5}$$

If it be assumed that the total volume of the electrolyte within the pore space is effective in conducting an electric current, then

$$\frac{\tau_s \psi_s}{\tau \psi} = S. \tag{6}$$

Since

$$\tau \psi = p. \tag{7}$$

Combination of Equations (5), (6), and (7) results in the equation

$$F_s = \frac{\tau_s^2}{pS}. \tag{8}$$

The above relation points out that, even for partial water saturations, the ratio of rock resistivity to electrolyte resistivity, F_s, times the water content, pS, should be directly related to the square of the tortuosity.

In order to explore the validity of Equation (8), the product of F_s and pS was plotted against the tortuosity on logarithmic coordinates. This plot is shown in Figure 4. The data are for two unconsolidated sands and two indurated sandstones from wells. From Figure 4, it is evident that the data on samples containing both oil and water fit Equation (8). This again suggests the presence of little, if any, electrolyte volume which does not contribute to the electric current.

Since Equation (6) was used in the derivation of Equation (8), the data shown in Figure 4 serve to verify Equation (6) as well as Equation (8). In order to illustrate the effect of variation of S on τ_s and ψ_s in Equation (6), the ratios τ_s/τ and ψ/ψ_s were plotted, on logarithmic coordinates, as functions of S for each of the four samples investigated. These plots are shown in Figure 5. The ratios τ_s/τ were determined experimentally and the ratios ψ/ψ_s were calculated from Equations (1) and (5).

The physical significance of these data is that when the water content is decreased, the increase in electrical resistance of a sample of reservoir rock is primarily due to a reduction in cross-sectional area of the electrolyte rather than to an increase in electrical path length. This is demonstrated graphically in Figure 5. For example, at water saturation of 30 percent the cross-sectional area, ψ_s, decreased on the average to one-seventh of the value at 100 percent water saturation while the tortuosity increased to twice the value at 100 percent water saturation.

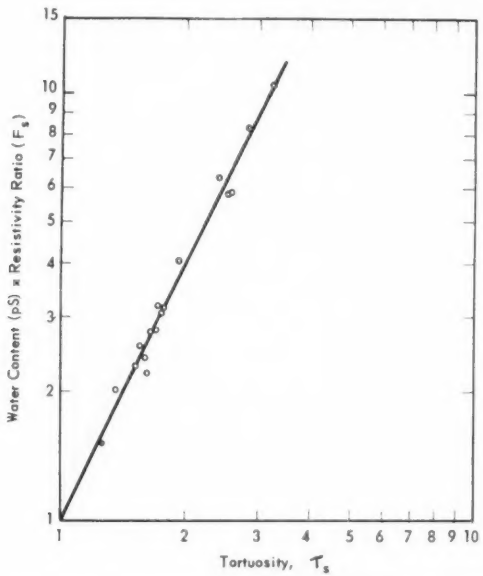

FIG. 4. Relation of water content times resistivity ratio to the tortuosity.

Since the data in Figure 5 appear to fall on straight lines on logarithmic coordinates, they may be represented by the equations

$$\left(\frac{\tau_s}{\tau}\right)^a = S = \left(\frac{\psi}{\psi_s}\right)^b \tag{9}$$

or

$$\left(\frac{\tau_s}{\tau}\right)^c = \left(\frac{\psi}{\psi_s}\right) \tag{10}$$

where a, b, and c are constants. These results may be used to express in geometric terms the saturation exponent used in the interpretation of the electric log.

Expression of the Saturation Exponent in Geometric Terms

Equations (2) and (8), and the empirical relationship of Equation (10) may be used to express the saturation exponent, n, in terms of τ_s/τ and ψ_s/ψ.

Equations (2) and (8) may be combined to give

$$\frac{F}{F_s} = S\left(\frac{\tau}{\tau_s}\right)^2. \tag{11}$$

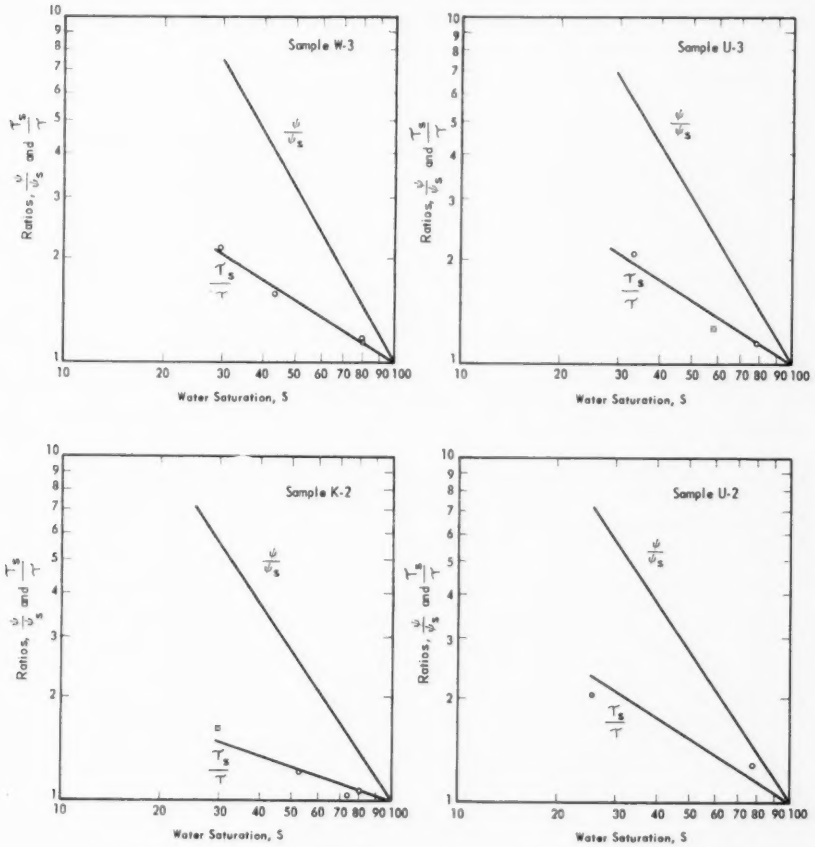

FIG. 5. Variation of tortuosity and calculated apparent cross-sectional area with water saturation for core samples.

Similarly, Equations (6) and (10) may be combined to give

$$S = \left(\frac{\tau_s}{\tau}\right)^{1-c}. \tag{12}$$

By substitution of this expression into Equation (11), the relation

$$\frac{F}{F_s} = S^{(c+1)/(c-1)} \tag{13}$$

is obtained.

A comparison of the latter equation with the empirical relationship which is customarily used in electric log interpretation,

$$\frac{F}{F_s} = S^n, \tag{14}$$

where n is the saturation exponent, demonstrates that n is given by

$$n = \frac{c + 1}{c - 1}. \tag{15}$$

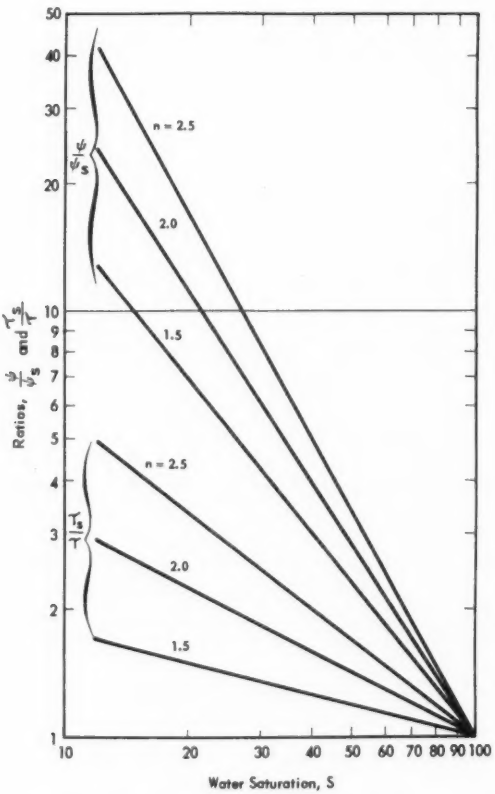

FIG. 6. Calculated variation of tortuous length and apparent cross-sectional area with water saturation for different values of "n."

By substitution in Equation (10), it is found that

$$\left(\frac{\tau_s}{\tau}\right)^{(n+1)/(n-1)} = \psi/\psi_s. \tag{16}$$

By substitution of various values of n into Equation (16) and combining with Equation (6), the effect of n on the geometry of the conducting electrolyte, which is reflected by changes in τ_s/τ and ψ/ψ_s at various saturations, may be investigated. This is demonstrated in Figure 6 for assumed values of n of 1.5, 2.0, and 2.5.

From Figure 6 it is evident that an increase in the value of the saturation exponent, n, results in increases both in τ_s/τ and in ψ/ψ_s. At low values of n, the ratio τ_s/τ increases only a relatively small amount with decreasing electrolyte saturation. Consequently, for this case, most of the increase in resistivity accompanying a decrease in electrolyte saturation may be attributed to a decrease in apparent cross-sectional area of the electrolyte. At high values of n the ratio τ_s/τ becomes more important in influencing the resistivity as the electrolyte saturation is varied, but even at high values of n, the decrease in apparent cross-sectional area is more important than is the increase in tortuosity.

CONCLUSION

1. A redetermination of the tortuosities of brine-saturated sandstones has shown that the resistivity factor, F, the tortuosity, τ, and the porosity, p, are related by

$$F = \tau^2/p.$$

2. Tortuosity measurements of the aqueous phase in sands containing both electrolyte and hydrocarbons show that the tortuosity of the interstitial water, τ_s, the resistivity ratio, F_s, the electrolyte saturation, S, and the porosity, p, are related by

$$F_s = \frac{\tau_s^2}{pS}.$$

3. The saturation exponent, n, customarily used in interpretation of the electric log, may be expressed in terms of tortuosity and apparent cross-sectional area of the electrolyte through which electric current flows.

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COMMENTS ON PAPER, "RESISTIVITY OF SANDSTONES AS RELATED TO THE GEOMETRY OF THEIR INTERSTITIAL WATER" BY F. M. PERKINS, JR., J. S. OSOBA AND K. H. RIBE

M. R. J. WYLLIE† AND A. J. DE WITTE†

The experimental data presented in the above paper are of interest and value. Nevertheless, it is of some importance to note a basic claim made by the authors; namely, that they can measure the tortuosities of porous media experimentally. This claim, we believe, cannot be substantiated. We shall demonstrate below why we think the claim is unjustified. It is necessary first to point out that the paper under discussion is based on the reasoning presented originally by Winsauer, Shearin, Masson and Williams. Thus what is said of the present paper applies with equal strength to the earlier work.

The method of measurement used in both papers is that of detecting electrometrically the change of chloride ion concentration with time. In the Winsauer et al. paper it was chloride ion build-up; in the Perkins et al. paper it is chloride ion reduction. Whichever scheme is used, the curves of concentration (emf) versus time reflect changes caused by ionic migration in an electrolyte under the influence of a potential gradient. Material transport of this kind is governed by Faraday's laws. The quantity of material transported is related to current and time in the following manner:

$$Q = KIt \tag{1}$$

Here

Q = total quantity of ion transported; i.e., chloride or acetate ion.

I = current

t = time

K = constant

Consider two different cores tested in the apparatus (Figure 1 of the Perkins et al. paper). Let these cores have the following properties:

	Sample 1	*Sample 2*
Porosity	P_1	P_2
Tortuosity	τ_1	τ_2
Apparent cross section [Perkin's Equation (1)]	Ψ_1	Ψ_2
Formation factor	F_1	F_2

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Considering now only the experimental method of Perkins et al., the amount of material to be transported through either sample at the time of arrival of the ionic boundary at the anode is the amount of chloride ion transported out of the core or the amount of acetate ion transported through the core. This quantity of chloride (or acetate) ion is given by Q = pore volume × concentration = $P \times c$ in any sample. With the subscripts referring to the individual samples: $Q_1 = P_1 \times c_1$ and $Q_2 = P_2 \times c_2$.

Since the concentrations, c, of salts used in both samples are identical we have:

$$Q_1/Q_2 = P_1/P_2 \tag{2}$$

From Equation (1)

$$Q_1 = KI_1t_1 \tag{3}$$

$$Q_2 = KI_2t_2 \tag{4}$$

The voltage, E, across the cell is held equal in both cases. Thus if $R1$ and $R2$ are the resistances of samples,

$$\frac{I_1}{I_2} = \frac{R_2}{R_1} = \frac{F_2}{F_1} \tag{5}$$

From Equation (1) of the Perkins et al. paper and Equation (5), it also follows that

$$\frac{I_1}{I_2} = \frac{F_2}{F_1} = \frac{\tau_2}{\tau_1} \cdot \frac{\psi_1}{\psi_2} \tag{6}$$

Dividing Equation (3) by Equation (4) and using Equations (2) and (6):

$$\frac{t_1}{t_2} = \frac{Q_1I_2}{Q_2I_1} = \frac{P_1}{P_2} \cdot \frac{I_2}{I_1}$$

$$= \frac{P_1}{P_2} \cdot \frac{\tau_1\psi_2}{\tau_2\psi_1} \tag{7}$$

From Equation (7) if follows that

$$\frac{t_1}{t_2} = \left(\frac{\tau_1}{\tau_2}\right)^2 \text{ only if } P = \tau\psi \text{ or if } P = \text{constant} \times \tau\psi.$$

In preparing the theoretical curves of Figure 5 of the Winsauer et al. paper, the assumption that $t_1/t_2 = (\tau_1/\tau_2)^2$ (and thus, also that $P = \tau\psi$) is implicitly made. The same relationship is given as Equation (4) of the Perkins et al. paper. In other words, Winsauer et al., and consequently Perkins et al., without being aware of it now define the concepts τ and ψ, hitherto loosely described as "average" length and cross section (ratio) of current, by the two equations $F = \tau/\psi$ and $P = \tau\psi$. In the paper of Perkins et al., not surprisingly, the experimental data are in accord

with these assumptions, i.e., if $P=\tau\psi$ and $F=\tau/\psi$ then $PF=\tau^2$. Logically this appears to be an example of petitio principii.

Equating t_1 and t_2 as is done by Winsauer et al. (and Perkins et al.) by matching experimental data with a theoretical curve (or by using experimental breakthrough times) strictly establishes only that, according to Equation (7)

$$P_1\frac{\tau_1}{\psi_1} = P_2\frac{\tau_2}{\psi_2} \tag{8}$$

Equation (8) may be written as

$$P_1F_1 = P_2F_2 \tag{9}$$

Since F_1 and F_2 can be measured independently, the experiments provide only a means of comparing *porosities*. If the porosity of the glass tubes in the "reference" experiment had been measured, this fact would have been clear to the authors. It is worth noting that experiments identical to those of the authors (except for the use of diffusion alone, i.e., without an added potential gradient) were reported in 1948 by Schofield and Dakshinamurti. These authors used their data correctly to determine the porosities of porous media effective in diffusion and conductivity, i.e., formation factors.

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GEOPHYSICS, VOL. XXI, NO. 4 (OCTOBER, 1956), PP. 1087-1099, 4 FIGS.

HEAT FLOW IN WEST TEXAS AND EASTERN NEW MEXICO*

EUGENE HERRIN† AND SYDNEY P. CLARK, JR.‡

ABSTRACT

Geothermal gradients are examined in West Texas and eastern New Mexico, and it is found that the gradients in the salt section of the Permian Salado formation are nearly uniform throughout the region. The values range from 7.70 to 9.00°C/km. Measured values of the thermal conductivity of rock salt are reviewed, and it is concluded that this quantity is most likely to be about 13×10^{-3} cal/cm sec °C., with an estimated uncertainty of ten percent. From these figures, the heat flow is found to be $1.1 \pm 0.1 \times 10^{-6}$ cal/cm² sec in this region.

INTRODUCTION

The internal thermal regime of the earth is of fundamental importance to geological and geophysical theory. The source not only of magmatism and metamorphic heat but also of orogenic forces is commonly sought in deep-seated thermal processes. For many years the efforts in this field were devoted to the collection of underground temperatures with the hope of discovering the "normal" rate of increase of temperature with depth, or "normal" geothermal gradient. It has become clear, however, that geothermal gradients may differ by a factor of ten in different places, and that the gradient may be different at different depths along any given vertical. A more useful quantity both for general theory and for the estimation of temperature beyond accessible depths is the heat flow, or amount of thermal energy emerging from the earth per unit area and unit time. This quantity is equal to the product of the vertical gradient of temperature and the local thermal conductivity.

Determinations of heat flow at a few dozen places show remarkably little variation; most values fall between 0.5 and 1.5 microcalories per square centimeter per second (Birch, 1954). The reliable determinations are so few in number and so irregularly distributed geographically that it is not yet possible to perceive any clear pattern to the results. Such theory as we have suggests that correlations between heat flow and major geologic and topographic features should exist, but the theory cannot be adequately tested until the number of reliable determinations of heat flow is substantially increased.

Several hundred measurements of temperature have been made in oil wells in the United States, and if even a few of these could be used for finding heat flow, a considerable addition to our knowledge would result. In many cases only statistical summaries of the data have been published; these have so far proved to be useless for the determination of heat flow. A more serious difficulty is en-

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countered in attempting to find the thermal conductivity appropriate to the geologic section in which the temperatures were measured. The conductivities of rocks range from 0.002 to 0.020 calories per centimeter-second-degree C, and despite continuing efforts, it is still not possible to make satisfactory estimates of the thermal conductivity of sandstones, shales, or limestones on the basis of lithologic descriptions. Direct measurements of the conductivity are required, but available cores rarely provide an adequate sample of the local lithology

It does appear possible, however, to make use of temperatures in evaporite sections. A preliminary survey showed that the gradients in the Salado salt section (Upper Permian) in West Texas and eastern New Mexico varied little over a wide area. This suggests that the average conductivity of the salt remains the

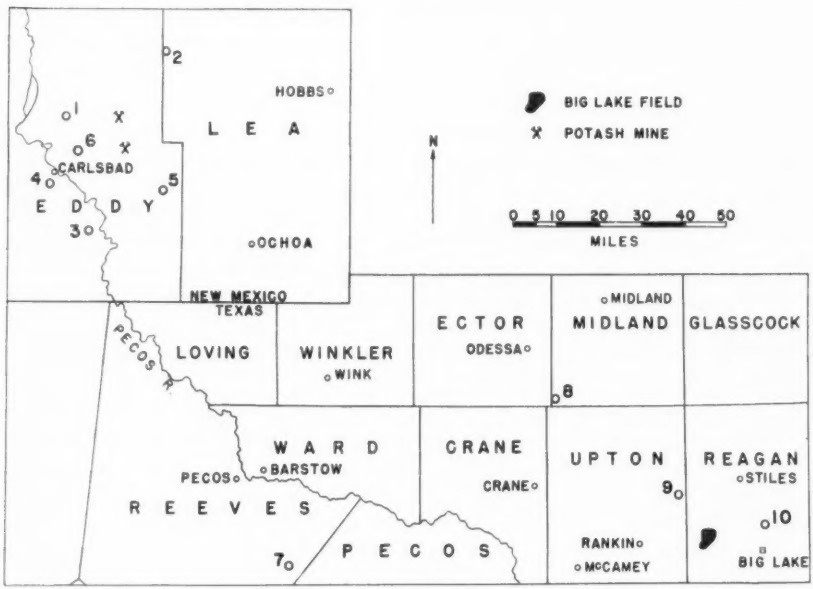

FIG. 1. Location map showing wells from which temperature data were taken.

Index of wells shown in Figure 1

1. Sandburg and Mills No. 1.
2. Cap Rock Oil and Gas No. 1.
3. Superior No. 1 Community.
4. New Mexico Producers and Refiners No. 1 Bluebird.
5. Marland-Ohio No. 1 Workman.
6. Getty No. 7 Dooley.
7. Gulf No. 1 Northrup.
8. Standard Potash No. 2 Test.
9. Donnelly and Gerke No. 1 University.
10. O'Reilly, Slack, and Owen No. 1 University.

same over the whole area. If a suitable value of this mean conductivity is found, it is then possible to find the heat flow in a considerable number of wells penetrating this formation.

This study was greatly advanced by the use of a continuous temperature log from the Gulf No. 1 Northrup well in Reeves County, Texas. Analysis of this log shows clear changes of gradient at lithologic boundaries and establishes a useful ratio between the mean conductivities of salt and anhydrite. Older temperature measurements, made with mercury thermometers at isolated points without regard for lithologic boundaries, are, of course, inadequate for demonstrating sharp changes of gradient. Nevertheless, useful results were obtained from these old data.

ACKNOWLEDGMENTS

We are indebted to Mr. Charles L. Jones of the U. S. Geological Survey for supplying us with a number of samples from the Ochoa series near Carlsbad, New Mexico. Mr. McLain J. Forman of New Orleans kindly provided samples of anhydrite rock from the cap rock of a Gulf Coast salt dome. We are particularly indebted to Mr. George W. Leney and Dr. James T. Wilson of the University of Michigan for permission to include their unpublished measurements of the thermal conductivity of rock salt in our summary. The temperature log of the Gulf No. 1 Northrop well was provided through the courtesy of Mr. C. D. Cordry of the Gulf Oil Co. Finally, we wish to express our appreciation to Dr. Francis Birch for advice in all phases of the work and for critically reviewing the manuscript.

TEMPERATURE GRADIENTS

The temperature data available for this work can be divided into two categories. In the first there is only one well, the Gulf No. 1 Northrup. Mr. C. D. Cordry of the Gulf Oil Co. kindly supplied a continuous temperature log of this well. The remaining data were, with one exception, taken from Hawtof (1930). In this second category, the temperatures were read with thermometers at intervals of 250 or 500 feet. Hawtof's measurements only accidentally fall at formation contacts, and hence they usually show no evidence of abrupt changes in the slopes of the temperature-depth curves. Smooth, although somewhat wavy curves would also fit the data. Sharp changes in gradient are inferred from theoretical considerations and are strikingly displayed by the results obtained from the Gulf No. 1 Northrup well. Keeping these facts in mind, temperature-depth curves were reconstructed from Hawtof's measurements with the introduction of abrupt breaks in slope at contacts in the manner shown in Figure 2.

In some of the wells, the temperature was measured at only one point in the salt section. In this case the gradient in the salt was found by extrapolating the gradients in the underlying and overlying sections to the contacts of the salt, thus giving the temperatures at those points. The gradients found in this way are less reliable than those found from two or more temperatures measured in the salt section, and are distinguished in the tabulated results. Examples of a "reliable" and an "unreliable" gradient in the salt are shown in Figure 2.

The interpretation of discontinuous temperature data requires considerable judgment, and it is impossible to present either the details of our calculations or complete discussions of individual wells in a short paper. We have tried to select wells in which the relation between gradients and lithology is clear and susceptible of only one interpretation. In the interest of brevity and for easy reference, our calculated gradients are collected in table 3 in a later section.

Gulf No. 1 Northrup Well, Reeves County, Texas.

This well is located in southeast Reeves County a few miles west of the Pecos County line. The well was drilled by the rotary method, but was left undisturbed for one year before the temperature measurements were made. Schlumberger Well Surveying corporation made a continuous temperature log of the well from the surface to 8,076 feet; a radioactivity log was available for the cased part of the well from the surface to 5,200 feet and both radioactivity and electric logs were

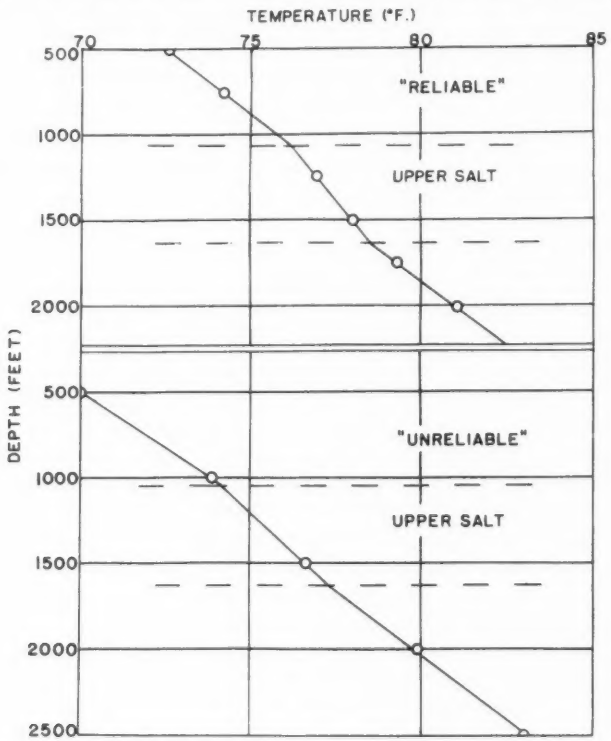

FIG. 2. Examples of "reliable" and "unreliable" Gradients in the Upper Salt, Big Lake Field. The "reliable" curve is from Big Lake-University Well No. 119, and the "unreliable" curve is from Big Lake-University Well No. 110.

available below this depth. The total depth of the well is now 18,609 feet.

A generalized stratigraphic section, compiled from several sources (Adams, 1944; Woods, 1940, Lang, 1935; Lang, 1939; and Carsey, 1935), was correlated with the well logs. Correlations with the radioactivity log above 5,200 feet were checked against the typical radioactivity log of the Ochoa series given by Russell (1941).

The temperature profile and gradients for this well are shown in Figure 3. The correlation between the gradient and the lithologies as determined from the well logs is striking, as is the sharpness of the change in gradient at several points. The value of a continuous temperature log is well-demonstrated by these results.

Big Lake Oil Field, Regan County, Texas.

There are three beds of salt in the Upper Castile formation in the Big Lake region, but only the uppermost one is thick enough to be detected on discontinuous temperature logs. Well logs given by Hennen (1929) and Sellards and Patton (1926) show that the thickness of the salt is uniformly 570 feet throughout the field. Hawtof (1930) gives the depth of the top of the salt section for all of the wells in which he measured temperatures.

Wells in Upton and Midland Counties, Texas.

Useful data were obtained from the Donnelly and Gerke No. 1 University well and from the Standard Potash No. 2 Test well in Upton and Midland Coun-

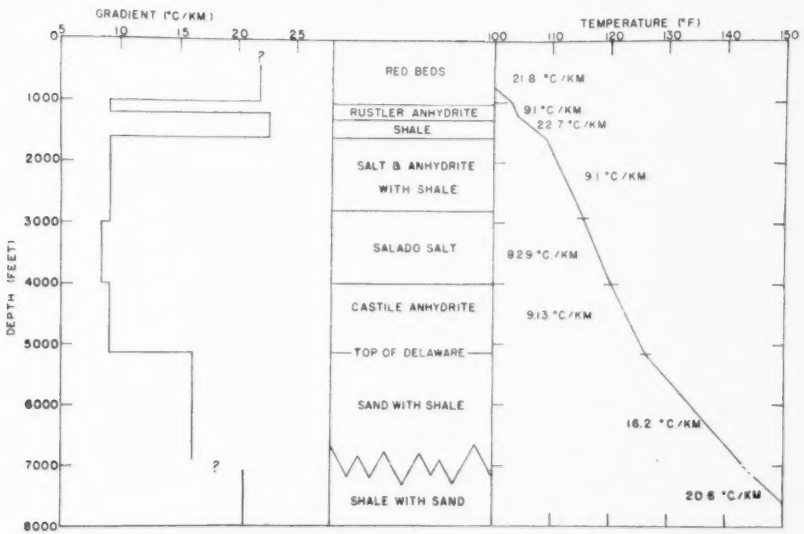

FIG. 3. Temperature, Geothermal Gradients, and Lithologies in the Gulf No. 1 Northrup Well, Reeves County, Texas. Lithology from electric and radioactivity logs.

ties respectively. Hawtof (1930) again gives the depth to the top of the salt in each well. The section in these wells was assumed to be the same as in the Big Lake field, since accurate knowledge of the thickness of the salt is unnecessary. In the former well the gradient is determined by two measurements of temperature in the salt section. In the latter, one measurement made in the salt is the deepest in the well.

Wells in Lea and Eddy Counties, New Mexico.

The stratigraphy in the northern part of the Delaware Basin is complicated by an unconformity at the base of the Rustler formation which cuts out most of the salt in this region. North-south and east-west cross sections by Kroenlein (1939) in the vicinity of Carlsbad show that over the Central Basin Platform a thick section of salt with little or no anhydrite is encountered. In the basin these relations are reversed, and anhydrite predominates over salt.

Reliable gradients were obtained in three of the six wells in New Mexico. In the Sandburg and Mills No. 1 well, the gradient was found in anhydrite; in the Marland-Ohio No. 1 Workman and the Getty No. 7 Dooley wells, data were obtained from a salt section with negligible amounts of anhydrite. In the latter well the temperatures were taken from Van Orstrand (1937); and Lang (1937) gives the section in the well. In the three remaining wells, the evaporite section is made up of both salt and anhydrite; without detailed sample logs it is impossible to determine the proportions of the two types of rock. Since the gradients are unreliable in all of these wells, highly accurate knowledge of lithology is unwarranted. We shall employ conductivities based on our best estimates of the lithologies in calculating the heat flow in these wells.

THERMAL CONDUCTIVITY

The geothermal gradients encountered in the salt section in the Permian Basin are rather uniform over the area examined (table 3). This suggests that the heat flow and the thermal conductivity in the salt are also nearly uniform. The alternative, to suppose that both of the latter quantities are changing in such a way as to leave the gradients unaffected, demands an improbably close balance between independent quantities. In order to calculate the heat flow in this region it is only necessary to estimate the conductivity of the salt section. Results of new measurements of thermal conductivity of other materials pertinent to this study will also be presented.

Conductivity of Rock Salt.

Because of the ease with which pure samples of salt can be obtained, one would expect to be dealing with a well-defined, uniform material; nevertheless, measurements of its thermal conductivity have not led to consistent results. Some of the discrepancies between the findings of various workers is doubtless due to real differences between the materials studied, but some must be due to experimental error. It is known that carefully prepared synthetic crystals

have conductivities that are higher than natural ones (Birch and Clark, 1940), and consequently little weight can be given determinations made on such materials in estimating the conductivity of rock salt.

Measurements of the thermal conductivity of rock salt as a function of temperature are shown in Figure 4. The measurements by Ballard, McCarthy, and Davis (1950) are on synthetic crystals; the remainder are on natural material. There is a tendency for the results to be concentrated about the curve representing the measurements of Birch and Clark (1940). The two values that fall well below this curve are probably erroneous. Most of the points above the curve represent measurements on single crystals, and their greater purity and perfection may account for the higher conductivity.

If we ignore the measurements made on artificial crystals and those which appear to be affected by experimental error, the results shown in Figure 4 suggest that the conductivity of rock salt is about 13[1] at a temperature of 20 to

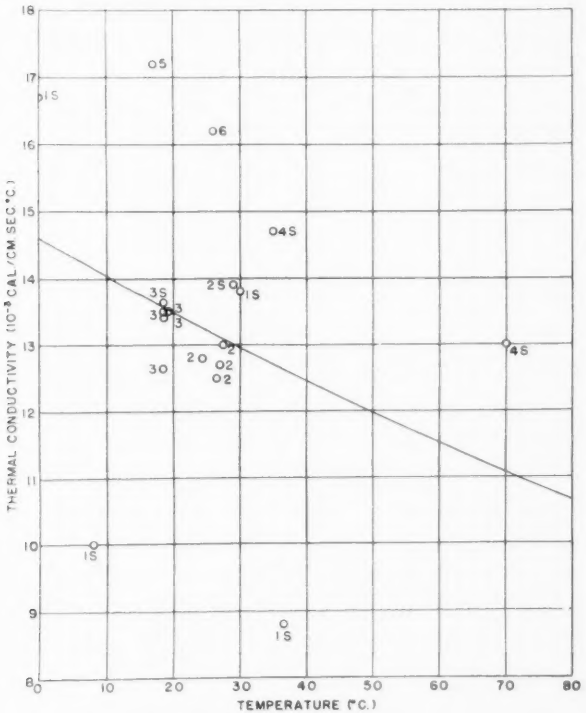

FIG. 4. Thermal conductivity of rock salt as a function of temperature. The curve is from Birch and Clark (1940). Other references: 1. Birch et al. (1942); 2. Present study (see table 2); 3. Unpublished measurements by George W. Leney; 4. Ballard, McCarthy, and Davis (1950); 5. Benfield (1939); 6. Coster (1947). Points marked with the letter *S* represent measurements on single crystals.

30°C. The only pertinent values that depart widely from this figure are those of Benfield (1939) and Coster (1947). Both of these measurements were made on natural rock salt with apparatus of proven reliability. It appears that rock salt may have a thermal conductivity considerably higher than 13, but on the basis of present data such values must be considered exceptional. We adopt 13 as the conductivity of rock salt, with an estimated uncertainty of ten percent.

Conductivity of Anhydrite.

Measurements of the conductivity of massive anhydrite rock are given in table 1. Specimens from the Loetschberg Tunnel in Switzerland and from the cap rock of a Gulf Coast salt dome gave fairly consistent results, but these samples were exceedingly pure, and their densities approached that of single crystals of the mineral. Specimens with porosity or containing small amounts of gypsum should have lower conductivities. This may account for the difference between Coster's (1947) results and the other values given in table 1. We adopt a value of 13.5 for the conductivity of pure anhydrite rock.

TABLE 1

THERMAL CONDUCTIVITY OF ANHYDRITE

Locality	Number of Samples	Mean Conductivity (cal/cm sec°C.)	Mean Density (gm/cm³)	Authority
Loetschberg Tunnel Switzerland	3	$13.4 \pm 0.3 \times 10^{-3}$	2.91	Clark & Niblett (in press)
Masjid-i-Sulaiman Iran	3	11.7 ± 1.2		Coster (1947)
Cap Rock Gulf Coast	3	13.7 ± 0.1	2.93	Present
Potash Mines Carlsbad, New Mex. (with minor halite inclusions)	3	12.9 ± 0.2	2.82	Present

New Conductivity Data.

The results of measurements of conductivity made for this study are collected in table 2. The rocks from New Mexico were kindly supplied by Mr. Charles L. Jones of the U. S. Geological Survey. These specimens were from the Rustler and Salado formations, and were chosen because of lithology rather than stratigraphic position. The measurements were made with the apparatus described by Birch (1950).

It appears from these data that the presence of small amounts of impurities has little effect on the conductivity of rock salt. Polyhalite is a poor conductor,

[1] Values of conductivity will henceforth be written as numbers with units 10^{-3} cal/cm sec °C. understood.

and our single sample of shale has a rather low conductivity for this type of rock. One specimen of dolomite has a conductivity of 10.6 compared with a mean value of 8.1 found by Birch and Clark (1945) for three samples from Crane County, Texas.

Conductivity of Other Sediments.

Once the heat flow in a well is found by means of the gradient in the salt section and the adopted conductivity of rock salt, it is possible to find the mean conductivity of other rock units by dividing the heat flow by the gradients obtained in other parts of the well. This provides a rough test of the "reasonability" of the heat flow. Measured values of the conductivity of shale range from

TABLE 2

RESULTS OF NEW CONDUCTIVITY MEASUREMENTS

Locality and Description	Conductivity (cal/cm sec °C.)	Density (gm/cm³)
Samples from Core taken near Carlsbad, New Mexico		
Anhydrite with ca. 30 percent halite	13.4×10^{-3}	2.49
Anhydrite with ca. 5 percent halite	13.2	2.92
	12.8	2.81
	12.7	2.75
Halite with ca. 5 percent polyhalite	12.8	2.11
Halite with ca. 5 percent clay	12.7	2.08
Polyhalite	3.7	2.76
	3.7	2.76
Dolomite	10.6	2.65
Salt Samples from Oklahoma (?)		
Polycrystalline salt	13.0	2.19
	12.5	2.17
Single crystal of salt	13.9	2.17
Permian basin		
Black shale (lower Permian)	2.2	2.41
Cap Rock, Gulf Coast		
Anhydrite	13.9	2.93
	13.8	2.93
	13.5	2.92

about 3.0 to 5.0, for sandstone from 4.8 to 8.1, limestone 5.0 to 7.3, and dolomite 8.1 to 13.2. (These data were taken from Birch et al., 1942; Mossop and Gafner, 1951; Bullard and Niblett, 1951; and Birch and Clark, 1945.)

We expect that the mean conductivity in an interval, as calculated from the gradients, should be in reasonable agreement with the figures given above. For heterogeneous sections a weighted mean conductivity must be used. For layered rocks the appropriate formula for the conductivity of a heterogeneous interval is $1/K = \sum_i w_i/K_i$, where K is the mean conductivity in the interval, K_i is the conductivity of the ith homogeneous bed, and w_i is the ratio of the thickness of the ith bed to the thickness of the entire interval. This formula is analogous to that used for calculating the resistance of electrical resistors in series.

HEAT FLOW

Geothermal gradients, assumed conductivities in the evaporite section, and resultant values of the heat flow are collected in table 3. With 1.1×10^{-6} cal/cm²sec for the heat flow in the Gulf No. 1 Northrup well, the conductivities given in table 4 are found for other strata in the well. The values for the clastic rocks are in reasonable agreement with the measured values mentioned in the preceding section, but the Castile anhydrite has a lower conductivity than that found for pure anhydrite rock. This discrepancy is presumed to be due to laminae of calcite which occur throughout the Castile formation. According to Adams (1944) the anhydrite layers are characteristically two or three times as thick as the calcite layers, and there are also beds of pure anhydrite up to several feet in thickness scattered irregularly through the section. We assume the calcite layers to have a

TABLE 3

GRADIENTS, CONDUCTIVITY, AND HEAT FLOW IN WEST TEXAS, AND EASTERN NEW MEXICO

Well Name	Geothermal Gradient in Evaporites (°C./km)	Conductivity (cal/cm sec °C)	Heat Flow (cal/cm² sec)
Reeves Co., Tex.			
Gulf No. 1 Northrup	*8.29	13×10^{-3}	$*1.1 \times 10^{-6}$
Regan Co., Tex.			
Big Lake-University			
103	*9.00	13	*1.2
106	8.80	13	1.1
110	9.84	13	1.3
112	9.15	13	1.2
115	*7.59	13	*1.0
118	*7.94	13	*1.0
119	*8.31	13	*1.1
124	8.5	13	1.1
125	8.3	13	1.1
126	*8.29	13	*1.1
127	*8.57	13	*1.1
O'Reilly-Slack-Owen-University No. 1	9.74	13	1.3
Upton Co., Tex.			
Donnelly and Gerke No. 1	*8.20	13	*1.1
Midland Co., Tex.			
Standard Potash No. 2 Test	9.4	13	1.2
Eddy Co., New Mexico			
Sandburg and Mills No. 1	*10.27	11.8[1]	*1.2
Superior No. 1 Community	10.12	11.8[1]	1.2
New Mexico Producers & Refiners No. 1 Bluebird	7.25	13	0.9
Marland-Ohio No. 1 Workman	*7.70	13	*1.0
Getty No. 7 Dooley	*8.02	13	*1.0
Lea Co., New Mexico			
Cap Rock Oil and Gas No. 1	9.2(?)	13	1.2(?)

* Reliable values.
[1] Anhydrite.

conductivity of 7 and the anhydrite 13.5. If the section consists of 30 percent calcite, its mean conductivity is 10.4; it is 11.4 if calcite layers make up 20 percent of the section. Agreement with the value of 11.8 calculated from the gradients is obtained by assuming about 15 percent calcite in the anhydrite. We adopt a conductivity of 11.8 for the Castile formation in order to estimate the heat flow in some of the wells in New Mexico which encountered no thick salt section.

In the Big Lake field the conductivity of the beds above the salt was calculated from the gradients by taking the heat flow to be equal to the mean of the reliable values in the salt section (1.1×10^{-6} cal/cm^{2}sec). The beds above the salt have a mean conductivity of 7.4, which is reasonable for a sequence of clastic rocks.

TABLE 4

CONDUCTIVITIES IN THE GULF NO. 1. NORTHRUP WELL

Interval	Conductivity (cal/cm sec °C.)
Red Beds above the Rustler	4.9×10^{-3}
Shale above the salt	4.7
Anhydrite	11.8
Shaley sand (Delaware Mtn. Gp.)	6.7
Sandy shale (Delaware Mtn. Gp.)	5.2

The mean value of the heat flow in the reliable wells in New Mexico is 1.1×10^{-6} cal/cm^{2}sec, but the heat flow in wells drilled through salt is systematically lower than that found in the anhydrite. Our value of the conductivity of the anhydrite may be too high, but until an opportunity for a detailed study of the conductivity of these rocks presents itself, the question must remain unsettled.

In all of the places examined the heat flow is found to be close to 1.1×10^{-6} cal/cm^{2}sec. This value is lower than the value of 1.4×10^{-6} found by Richardson and Wells (1931) in New Mexico, and considerably lower than the value 2.0×10^{-6} found by Birch and Clark (1945). The former result is based on a conductivity of anhydrite of 12.3, and Richardson and Wells give no source of this value. The heat flow found by Birch and Clark was obtained from gradients in the Big Lake University 1-B well, and measured conductivities of rocks from wells in Upton and Crane Counties, Texas. They found a gradient of 24°C./km between 2,500 and 6,500 feet, which is below the evaporite section. They assumed that the rocks in this interval were represented by samples of dolomitic limestones from the wells further west. These samples are not representative of the lithologies encountered between 2,500 and 6,500 feet in the Big Lake field, although they are probably of the same age. From the driller's log of this well (Hennen, 1929), the rocks in this interval are estimated to be: 7 percent sand, 5 percent anhydrite, 46 percent shale and silt, and 42 percent limestone and dolomite. Assuming conductivities of 6 for the sand (which contains some shale), 3 for the shale, 13.5 for the anhydrite, and 8 for the carbonates, we find the mean conductivity in this interval to be 4.5. It is likely that in some cases limestone was mistaken for dolo-

mite in the driller's log. If we assume that all of the rocks logged as carbonates are anhydrite with conductivity 13.5, the mean conductivity in the interval is found to be 5.0. The resulting heat flow is 1.1 or 1.2×10^{-6} cal/cm²sec depending on the assumed conductivity. The close agreement between this value and that obtained from the salt section is fortuitous, for driller's logs are not reliable indices of lithology and the values of conductivity that we have adopted are no more than guided guesses. Nevertheless the result shows that the heat flow of 2.0×10^{-6} found by Birch and Clark is improbably large, and that there is no serious disagreement between the heat flow in this part of the well and that in the salt section.

The gradient below 7,000 feet in this well is greater than 34°C./km (Birch and Clark, 1945). According to the driller's log the rocks below 7,000 feet are mainly carbonates, and such a high gradient is unexpected. We must conclude that either the temperatures are in error or the carbonates are extremely porous limestones of low conductivity (ca. 4). If the conductivity of the limestones were as high as 7, the heat flow would be about 2.4×10^{-6} cal/cm²sec. This requires that the conductivity of salt be about 29, which seems impossible.

CONCLUSIONS

On the basis of present data we conclude that the heat flow in West Texas and eastern New Mexico is $1.1 \pm 0.1 \times 10^{-6}$ cal/cm²sec. More accurate studies will be necessary if changes in heat flow from place to place within this region are to be established. The most serious error affecting our results arises from the lack of measured values of the thermal conductivity of the rocks in which the temperatures were measured. Our estimated uncertainty of ten percent should be sufficiently generous, but our results are subject to revision should future measurements prove our adopted value of the conductivity to be in error.

There is a definite correlation between geothermal gradient and lithology in regions in which formations of contrasting thermal conductivity are found. This correlation is best demonstrated by continuous temperature logs; measurements of temperature at isolated points cannot reveal abrupt changes of gradient. The low gradients in the salt sequence in the Permian basin persist over a large area; the "coolness" of the rocks in this region is due to the high conductivity of the evaporites.

It is fruitless to attempt to interpret temperature-depth curves without regard for lithology. In this connection we are faced with a paradoxical situation, for a preponderance of data on underground temperatures comes from wells for which there is no modern lithologic control. Our knowledge of heat flow could be greatly enhanced by modern data on both temperature and conductivity from a relatively small number of oil wells. It is to be hoped that opportunities for new measurements of these quantities will be recognized by geologists in charge of drilling, and that continuous temperature logs, as well as adequate cores from the logged section, will become available in the future.

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GEOPHYSICS, VOL. XXI, NO. 4 (OCTOBER, 1956), PP. 1100–1110, 6 FIGS.

MAGNETIC PROPERTIES OF MAGNETITE*

V. BHASKARA RAO†

ABSTRACT

Hysteresis characteristics of a magnetite sample from Gudur area in South India have been studied up to a maximum magnetizing field of 375 oersteds. The apparatus used was the same as developed by Bruckshaw and Rao. The studies have shown that the susceptibilities of rocks are mainly dependent on the magnetite contained in them. Variations of susceptibility of magnetite with its grain size, its purity and its distribution in an inert matrix provide the explanation for the enormous range of rock susceptibilities usually encountered.

INTRODUCTION

Most of the rock-forming minerals, except a few containing the ferric iron and manganese, are magnetically inert. Their contribution to the magnetic behaviour of a rock has been found to be negligibly small. Among the magnetic minerals, magnetite—the most strongly magnetic of them—received close, attentive study by a number of workers over the years. Since Weiss (1896) made his classic studies upon magnetite crystals at fields nearly as weak as the earth's, several authors have studied the various aspects of magnetic behaviour of magnetite.

It is generally agreed that the susceptibility of rocks mainly depends on the volume content, the demagnetisation factor and the susceptibility of the ferromagnetic minerals contained in them. Volume content of the ferromagnetic minerals could be estimated by chemical analyses and other methods. The values generally adopted for the demagnetisation factor on the assumption of spherical or prolate spherical particles are not much divergent from the true values. In such a case it can be seen that the great range of susceptibilities of rock observed must be due to the variations of susceptibility of the ferromagnetic minerals themselves. Hence a study of them, especially of magnetite, should prove very helpful in understanding the results of magnetic determinations on rocks.

Results of the study of hysteretic characteristics of a magnetite sample from Gudur area (South India) carried out by the author in the geophysical laboratories of the Andhra University are reported here. The apparatus used was the one developed by Bruckshaw and Rao (1950). Magnetic properties and their variations up to a field of 375 oersteds have been studied.

EXPERIMENTAL TECHNIQUE

Preparation of Samples

The magnetite was crushed and sieved to various mesh sizes ranging from +20 to +140, so that the variation of the magnetic properties with the grain

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size could be studied. The magnetite powder was then mixed with Plaster of Paris, which forms an inert matrix. Different amounts of magnetite were mixed with this inert material to give different packing densities. This mixture was moistened with water and cast in a Tufnol cast to give cubic specimens of two cms side and allowed to set. After a time, the specimen was taken out by unscrewing the sides of the cast and allowed to dry. A summary of the values of packing density, percentage of magnetite by weight and the average grain size of the magnetite particles contained in the specimens numbered S_1 to S_{14} is given below in Table I.

TABLE I

Grain size Microns	Specimen No.	Percent of Magnetite by weight	Packing Density	H_c Oersteds	$I_r \times 10^2$ Gauss
476	S_1	90	2.32	67	195
	S_2	70	1.82	69	30
	S_3	50	1.16	75	17
	S_4	40	0.86	79	—
	S_5	30	0.55	83	14
264	S_6	70	1.71	60	—
	S_7	50	1.06	68	18
	S_8	30	0.52	75	14
169	S_9	70	1.60	83	78
	S_{10}	50	1.03	—	26
	S_{11}	30	0.51	95	24
114	S_{12}	50	0.98	83	49
	S_{13}	10	1.44	105	4
96	S_{14}	50	0.88	87	37

Method of Drawing the I–H Curves

A differential voltage proportional to dI/dt, is set up in the pick-up coil system, when a specimen is inserted in the magnetic field produced by the Helmholtz coils. This voltage is fed to the vertical (Y) deflecting plates of a cathode-ray oscillograph, while a small voltage tapped across a fixed resistance in series with the field coils is used as the input for the horizontal (X) deflecting plates. The resultant picture is of the shape shown in Figure 1, in which the X and Y axes are obtained by disconnecting successively the Y and X inputs respectively. The X-axis represents the magnetic field from -375 to $+375$ oersteds, which is the maximum field used in the present studies. The field axis is divided into a conveniently large number (usually 20) of equal parts. So, at intervals of 37.5 oersteds, the deflections dI/dt are measured and divided numerically by the corresponding cos ωt values. The quotients thus obtained are proportional to dI/dH at these field intervals. Now, these proportionate values of dI/dH are plotted against their corresponding intervals of dH giving two curves corresponding to the two halves of dI/dt curve. Integration of these curves from $+H_0$ to $-H_0$ at intervals of dH gives the areas; and an area at any value of H is the sum of all the areas for all the preceding values of H and is proportional to the intensity of magnetisation at that value of H. These values of successively integrated and continuously

added areas are then plotted against the corresponding values of H giving the I-H curves. The values of I thus plotted are in arbitrary units of areas. These can be converted to absolute units of I by calibrating the vertical deflections with the aid of a search coil.

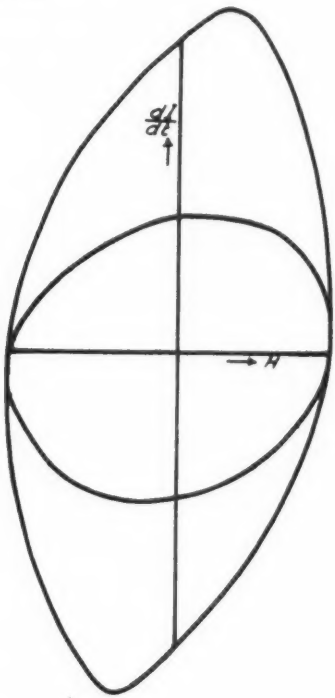

FIG. 1. dI/dt, H curve as obtained on the cathode-ray oscillograph screen.

Calibration of Vertical Deflections

Calibration to convert the vertical deflections on the cathode-ray oscillograph into absolute values of intensity of magnetisation is achieved by replacing the cubical specimen by an equivalent current carrying magnetic shell. A bakelite cube of two cms side is wound closely with 40 S.W.G. double cotton covered wire and is used to replace the magnetite specimen. For various currents sent through the coil, the vertical deflections on the cathode-ray oscillograph are measured. The intensity of magnetisation of such a current carrying shell is obtained by the product of the current (i) in electromagnetic units and the number (n) of turns of wire per unit length on the coil. Hence the intensity of magnetisation per unit length of deflection on the cathode-ray oscillograph screen is obtained.

Taking the scale factors of $(dI/dH)-H$ graph and the $I-H$ graph and the diminution and magnification factors involved in the photography into consideration, a conversion factor of 1.14 was arrived at. The total area at any value of H multiplied by this conversion factor gave the value of intensity of magnetisation for that H.

RESULTS AND THEIR DISCUSSION

Table I summarises the fourteen specimens studied. The specimens are prepared such that for the same grain size of magnetite different packing densities are also obtained, thus facilitating a study of the variation of magnetic properties with variations in grain size and packing density. Variations of coercivity H_c and remanence I_r with percentage of magnetite by weight for a fixed grain size of the magnetite particles are plotted in Figure 2. The coercivity variation is nearly linear—a gradual increase of coercivity with decreasing percentage of magnetite.

On the other hand, the remanence increases with increase in percentage of magnetite; this increase is gradual in the initial stages and then becomes much sharper. The increase in remanence beyond about 50 percent of magnetite by weight is as much as two to five times the values at less than 50 percent depending upon the grain size of the magnetite.

The variations of the different hysteretic parameters are summarised in Table II. In the third column of this table are shown the values of H_m, i.e., the magnetic field at which the susceptibility value is maximum. This is obtained by drawing a vertical line through the peak on the $(dI/dH)-H$ graph. In the last column, R represents the ratio of the maximum susceptibility to that at zero field and is a characteristic of the material.

TABLE II

Grain size in microns	H_c oersteds	H_m oersteds	$I_r \times 10^3$ gauss	R
476	—	113	17	1.26
264	68	120	18	1.26
169	69	131	26	1.35
114	83	158	49	1.35
96	87	169	—	1.46

These results are represented diagrammatically in Figure 3. The linear relationship of increasing coercivity with decreasing grain size is in good agreement with the observations of other workers. The other parameters H_m, I_r and R also show an increase with decrease in grain size. In the case of remanence, however, the rise is much steeper below a grain size of about 250 microns than in the case of H_m and R. Variations in R are not significant enough to allow any reliable conclusions to be drawn. This factor varies very little in the case of rocks also, as was reported by Bruckshaw and Rao (1950).

Variations of density of magnetisation $(4\pi I)$ and the permeability (μ) are

TABLE III

VARIATION OF DENSITY OF MAGNETISATION AND PERMEABILITY WITH PACKING DENSITY FOR 476 MICRONS GRAIN SIZE

H oersteds	$4\pi I$ gauss	Permeability	$4\pi I$ gauss	Permeability	$4\pi I$ gauss	Permeability	$4\pi I$ gauss	Permeability
37.5	236.2	7.30	42.95	2.15	23.81	1.64	20.71	1.55
75.0	279.7	4.73	55.60	1.74	30.88	1.41	26.09	1.36
112.5	320.6	3.85	67.79	1.60	37.60	1.33	32.86	1.29
150.0	359.0	3.39	79.30	1.53	43.87	1.29	38.43	1.26
187.5	395.5	3.10	90.46	1.48	49.79	1.27	43.73	1.23
225.0	429.3	2.91	100.7	1.45	55.49	1.25	48.68	1.22
262.5	460.5	2.75	110.5	1.42	60.84	1.23	53.35	1.20
300.0	488.5	2.63	119.8	1.40	65.75	1.22	57.81	1.19
337.5	514.0	2.52	128.3	1.38	70.42	1.21	61.95	1.18
375.0	536.3	2.43	136.0	1.36	74.63	1.20	65.85	1.17
Fe_3O_4 gm/cm³	2.32		1.82		1.16		0.55	

calculated from the results and shown in Tables III and IV. These values are calculated at intervals of 37.5 oersteds up to the maximum field of 375 oersteds. Table III gives their variation with packing density for particles of average grain size of 476 microns. For any packing density, the density of magnetisation increases and the permeability decreases with increasing magnetic field. It may also be seen that for a fixed magnetising field, the density of magnetisation and permeability decrease with decreasing packing density.

Table IV summarises the variations of the density of magnetisation and the permeability with grain size. For a particular value of the magnetic field, the permeability increases with decrease in grain size. Such an increase would be more in magnitude but for the fact that the change with grain size was not studied at the same value of packing density. From these tables the variation of apparent susceptibility of magnetite with the magnetic field could be deduced.

TABLE IV

VARIATION OF DENSITY OF MAGNETISATION AND PERMEABILITY WITH GRAIN SIZE

H oersteds	Fraction 1 −20 +40 mesh		Fraction 2 −40 +60 mesh		Fraction 3 −60 +100 mesh		Fraction 4 −100 +120 mesh		Fraction 5 −120 +140 mesh	
	$4\pi I$ gauss	Permeability	$4\pi I$ gauss	Permeability	$4\pi I$ gauss	Permeability	$4\pi I$ gauss	Permeability	$4\pi I$ gauss	Permeability
37.5	23.81	1.64	26.20	1.70	39.25	2.05	63.66	2.70	48.98	2.31
75.0	30.88	1.41	34.86	1.47	49.83	1.66	79.97	2.07	61.48	1.82
112.5	37.60	1.33	42.85	1.38	60.81	1.54	95.23	1.85	73.18	1.65
150.0	43.87	1.29	50.36	1.34	71.15	1.47	109.5	1.73	85.53	1.57
187.5	49.79	1.27	57.66	1.31	80.91	1.43	123.0	1.66	96.05	1.51
225.0	55.49	1.25	64.62	1.29	90.09	1.40	135.8	1.60	106.0	1.47
262.5	60.84	1.23	71.45	1.27	98.56	1.38	147.8	1.56	115.4	1.44
300.0	65.75	1.22	74.05	1.26	106.3	1.35	159.1	1.53	124.3	1.41
337.5	70.42	1.21	79.87	1.24	113.5	1.34	169.8	1.50	132.5	1.39
375.0	74.63	1.20	91.16	1.24	120.1	1.32	180.3	1.48	140.1	1.37
Fe_3O_4 gm/cm³	1.16		1.06		1.03		0.98		0.88	
Grain Size microns	476		264		169		114		96	

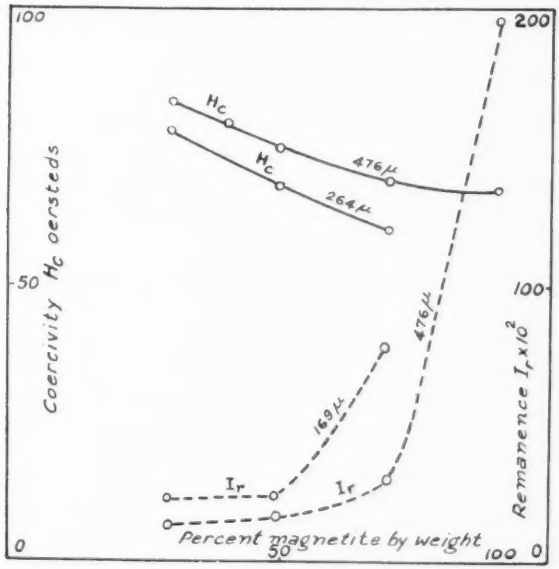

FIG. 2. Variation of remanence and coercivity with percentage by weight of magnetite.

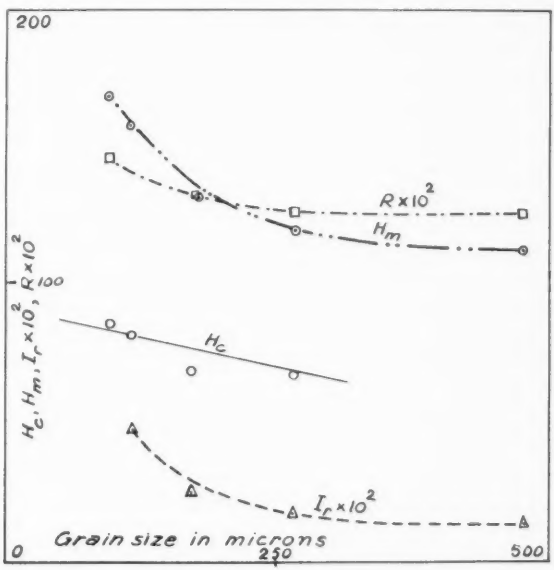

FIG. 3. Variation of H_c, H_m, I_r, and R with grain size.

The apparent susceptibility variations for a few specimens over the entire magnetic field range are shown in Table V.

The calculations of the susceptibility values are rounded off consistent with the accuracy of observations. The general trend of the variations is an increase with decreasing magnetic field. The increase of susceptibility is slow in the initial stages, becoming steeper as the field is further reduced. These results of susceptibility variation with magnetic field plotted in Figure 4 confirm in a large measure the earlier observations of Steinmetz (1892), Weiss (1896), and others. Determi-

TABLE V

H Oersteds	Susceptibility $K \times 10^3$ for			
	S_1	S_2	S_7	S_{12}
37·5	500	90	60	140
75·0	300	60	40	90
112·5	230	50	30	70
150·0	190	40	30	60
187·5	170	40	30	50
225·0	150	40	20	50
262·5	140	30	20	50
300·0	130	30	20	40
337·5	120	30	20	40
375·0	110	30	20	40

nations of susceptibility at fields lower than 37.5 oersteds are beyond the means of the present apparatus, but considering the good agreement of results in the field region studied, it may be stated that on extrapolation the behaviour at low fields will also be conformable.

Another interesting aspect of the susceptibility of magnetite is its variation with percentage of voids. The following table shows results of susceptibility variation with percentage of voids for different magnetic fields.

Figure 5, which shows these results graphically, is in marked agreement with the curves produced by Slichter (1929). It appears that as the magnetic field is decreased, the rise in susceptibility with decreasing percentage voids becomes more pronounced. As no investigations could be carried out on single crystals or cubes of magnetite itself, the full effect of pulverisation reported by Slichter (1929) and by Herroun (1943), among others, could not be verified.

The variation of susceptibility with percentage by weight of magnetite con-

TABLE VI

Specimen No.	Susceptibility $K \times 10^3$ for H=			Percent Voids
	37·5	75·0	300·0	
S_1	500	300	130	10
S_2	90	60	30	30
S_3	50	30	20	50
S_8	40	30	20	70

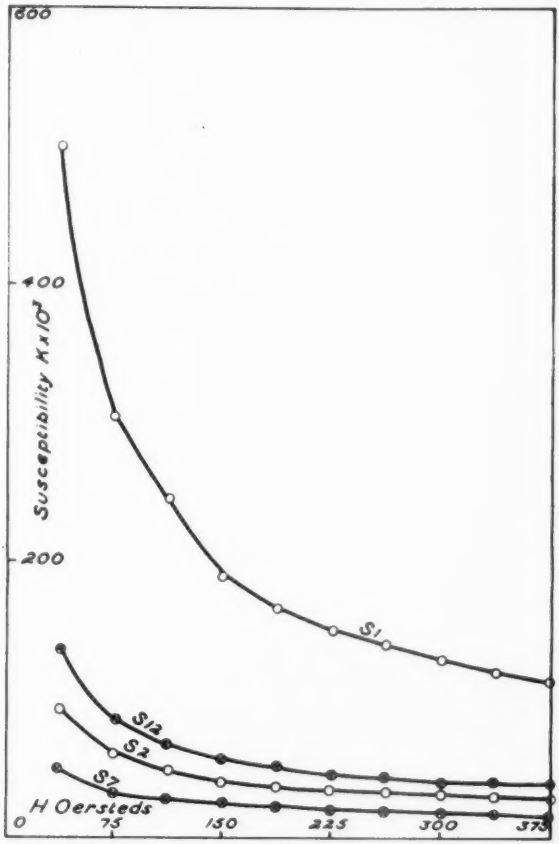

FIG. 4. Variation of magnetic susceptibility with field.

tained in the specimens is shown in Figure 6. The steep rise of susceptibility at higher percentages of magnetite content resembles closely the curves of Werner (1945) for ores rich in magnetite. Evidently, a linear relation does not hold; perhaps, a power law may prove more useful to express the relationship. However, no curve-fitting is attempted here due to insufficiency of data. It may also be noted that at the value of 50 percent of magnetite the susceptibility increase is about 50×10^{-3} for a decrease in grain size of 476 to 96 microns.

Though the susceptibility-field curve could not be traced below a magnetic field of 37.5 oersteds, it seems obvious that there would be a maximum susceptibility value below this field and that this maximum occurs at a field lower than the one obtained in the case of rocks.

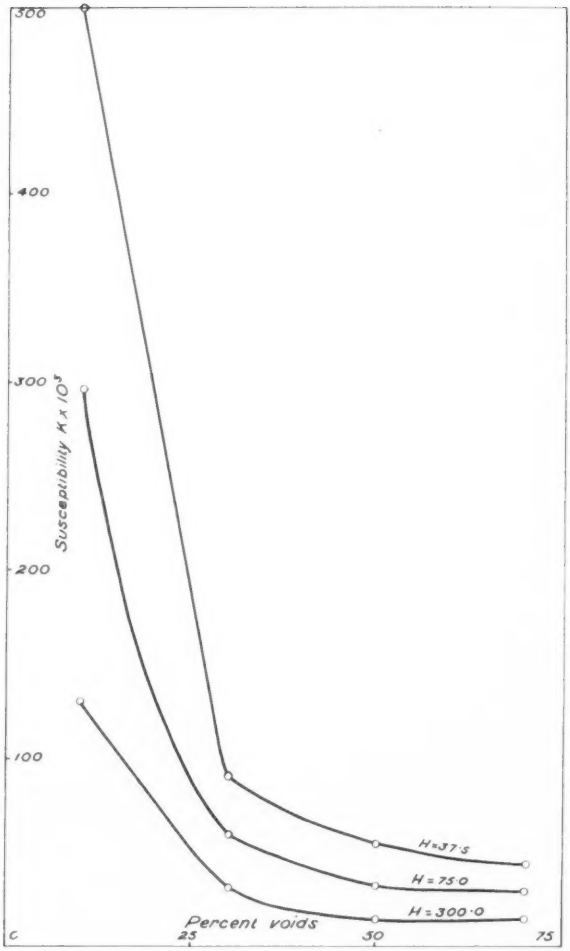

FIG. 5. Variation of magnetic susceptibility with percentage voids.

Experiments on crushed powders are easy and quick to conduct. They have the added advantage that variations of the magnetic parameters with grain size and packing density can be readily studied. Specimens in which the magnetite is as much disseminated as it is in rocks can be produced. However, it can be seen that the susceptibility is considerably reduced with increase in percentage voids. This fact is evident from Figure 5, in which the susceptibility variation with percentage voids is shown. It is observed that a reduction of percentage

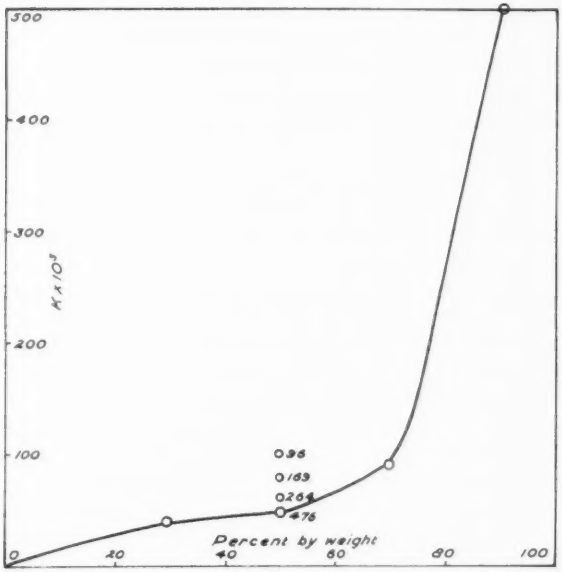

FIG. 6. Variation of susceptibility with percentage by weight of magnetite.

of voids from 30 to 10 increases the susceptibility by as much as four to five times. This variation appears to offer an explanation for the high susceptibility values obtained for solid specimens.

CONCLUSIONS

Briefly, the results of the investigations may be stated as follows:

1. Coercivity increases linearly with decrease in percentage by weight of magnetite and decrease in grain size of magnetite. This increase of coercivity with smallness of grain size explains the high coercivities encountered in most of the magnetically "hard" effusives ejected from volcanoes and cooled rapidly.

2. Remanence increases with increasing percentage of magnetite and decreasing grain size. This behaviour, when extended to magnetic fields as low as that of the earth, points to the important role that the determinations of natural remanent magnetism play in interpretations of magnetometric prospecting data.

3. The field at which maximum susceptibility occurs increases with decrease in grain size.

4. The ratio of the maximum susceptibility to that at zero field is nearly constant. The same is observed to be true in the case of rocks also.

5. The variation of susceptibility of magnetite shows an increase with decrease in magnetising field in the range of magnetic fields employed. The curves, though not extended to lower fields, point to a lower field at which maximum

susceptibility occurs, than in the case of rocks. The susceptibility-field curves of both magnetite and rocks follow similar trends, indicating that sucseptibility of a rock is determined mainly by its magnetite content.

6. Susceptibility increases rapidly with increasing magnetite content. There is a good agreement between these curves at higher percentages of magnetite content and those of Werner for ores rich in magnetite. It is believed that a power law expression may hold for this variation.

7. Susceptibility of magnetite is considerably reduced by crushing the material to powder form. This explains the high susceptibility values obtained for solid specimens.

Conclusion 5 is valid in the range of magnetising fields viz; 37.5 to 375 oersteds employed in these experiments. Both Puzicha (1941) and Slichter (1929) have obtained similar curves in this field range. However, at some field below 37.5 oersteds there would be the maximum susceptibility value; and any further decrease in magnetising field decreases the susceptibility until at fields very near to that of the earth the initial susceptibility value is reached. Werner's curves have not been extended, I believe, beyond the k_{max} field. The author has further observed (from experiments on rocks from the South Sydney Basin area) that the susceptibility-field curve for rocks follows closely the general trend of that of magnetite. This conclusion is in close agreement with the observations of Takagi (1913).

ACKNOWLEDGMENTS

The author thanks Dr. B. S. R. Rao for guidance during the course of the work and the Andhra University for the award of a research fellowship. He also expresses his thanks to Dr. H. Narain of the Department of Geology and Geophysics, the University of Sydney for valuable discussion and helpful suggestions while submitting this work as part of his thesis for the degree of Doctor of Philosophy of the University of Sydney.

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PATENTS

O. F. RITZMANN†

ELECTRICAL PROSPECTING

U. S. No. 2,741,736. M. Puranen and A. A. Kahma. Iss. 4/10/56. App. 8/31/54. Assign. Canadian Airborne Geophysics Ltd.

Method for Inductive Prospecting. An airborne electromagnetic prospecting system having a transmitting coil in the airplane and also an auxiliary coil in the airplane arranged to neutralize the out-of-phase component due to eddy currents in the airplane structure, the secondary field due to earth anomalies being picked up by a receiving coil in a towed bird whose signals are transmitted to the airplane by radio.

U. S. No. 2,744,232. E. N. Shawhan, M. J. Relis and J. Brown. Iss. 5/1/56. App. 3/6/52.

Magnetic and Conducting Materials Detector. A metal detector having a pick-up coil and a square-wave-excited energizing coil whose axis is perpendicular to and bisects the pick-up coil, and with the pick-up coil connected to an amplifier and phase discriminator.

GEOCHEMICAL PROSPECTING

U. S. No. 2,742,574. P. B. Weisz. Iss. 4/17/56. App. 12/12/51. Assign. Socony Mobil Oil Co., Inc.

Method for Detection of Hydrocarbons. A geochemical prospecting method in which soil gas samples are introduced into a Geiger counter and the quenching characteristic measured, quenching being indicative of hydrocarbons having at least two carbon atoms.

U. S. No. 2,742,575. E. E. Bray. Iss. 4/17/56. App. 7/14/52. Assign. Socony Mobil Oil Co., Inc.

Geochemical Exploration Method. A method of geochemical prospecting in which earth samples are extracted with a hydrocarbon solvent and the infrared transmission of the extract measured in the range 12 to 14 microns, absorption at 12.35 and 13.40 microns indicating hydrocarbons of petroleum origin.

GRAVIMETRIC PROSPECTING

U. S. No. 2,740,961. J. M. Slater. Iss. 4/3/56. App. 7/9/47. Assign. Sperry Rand Corp.

Stable Reference Apparatus. A gyro-maintained horizon in which the gyro is urged into the proper orientation by signals detecting the radar-reflection discontinuity between sky and earth at the horizon or by the discontinuity between infrared radiation received from the sky and the earth at the horizon.

U. S. No. 2,741,854. R. E. Jasperson. Iss. 4/17/56. App. 11/24/52.

Vertical Seeking Apparatus. A pendulous magnetic suspension having opposing hemispherical poles and a damping ring with baffles and partially filled with liquid.

U. S. No. 2,744,335. B. Litman. Iss. 5/8/56. App. 6/14/51. Assign. American Bosch Arma Corp.

Gravity Pendulum Device. A device for correcting accelerations other than gravity and having a motion-detecting impedance bridge which controls current through a correcting solenoid.

† Gulf Oil Corporation, Patent Department.

MAGNETIC PROSPECTING

U. S. No. 2,741,853. W. C. Anderson. Iss. 4/17/56. App. 8/25/44. Assign. U.S.A.

Magnetometer Compass. A flux-gate compass having two mutually perpendicular flux gate elements excited from a common oscillator and whose amplified outputs are respectively impressed on vertical and horizontal plates of a c-r tube.

U. S. No. 2,743,415. K. G. Williams and E. W. Frowe. Iss. 4/24/56. App. 9/30/46.

Gradiometer. A magnetic gradiometer having a high-permeability core with a pair of coaxial closely-spaced coils whose second harmonic is observed and which are balanced by potentiometers and condensers connected to the coils and also having gradient neutralizing coils on an outer shield.

U. S. No. 2,743,416. J. M. Kelly, Jr. Iss. 4/24/56. App. 3/12/52. Assign. U.S.A.

Magnetic Field Measuring Device. A magnetometer for strong magnetic fields having a thin high-permeability core which is alternately magnetized to saturation and the voltage pulses observed on a c-r oscilloscope and with the core also in a calibrated solenoid whose current is adjusted so that symmetrical pulses appear on the oscilloscope.

U. S. No. 2,744,235. G. Breit. Iss. 5/1/56. App. 2/4/46.

Magnetic Field Extrapolating Apparatus and Method. An automatic device for obtaining the configuration of a magnetic field at a plane other than that on which the field is known by setting up an array of a-c electromagnets excited to produce the known field configuration and measuring the field on other traverses with a search coil.

RADIOACTIVITY PROSPECTING

U. S. No. 2,740,900. R. J. Ruble and A. L. Tirico. Iss. 4/3/56. App. 8/22/52. Assign. Texaco Development Corp.

Radiation Detector. A radiation detector having an interaction membrane which releases low-energy electrons in response to the radiation and a photomultiplier tube which amplifies the low-energy pulse.

U. S. No. 2,741,708. F. C. Armistead. Iss. 4/10/56. App. 4/27/51. Assign. Texaco Development Corp.

Radiation Detection. A radioactivity detector which differentiates between low and high energy radiation and having a proportional counter in a high axial magnetic field so that secondary electrons from low energy radiation will have a short radius curved path and produce more ionization than electrons from high energy radiation.

U. S. No. 2,741,709. A. L. Tirico and R. J. Ruble. Iss. 4/10/56. App. 4/26/52. Assign. Texaco Development Corp.

Detector for Indicating Spectral Distribution of Penetrative Radiation. A device for detecting energy groups of penetrating radiation having a series of multiple-cathode plates of increasing absorption and which are separately connected to pulse-detecting circuits.

U. S. No. 2,742,576. R. A. Dandl. Iss. 4/17/56. App. 2/14/52. Assign. U.S.A.

Portable Scintillation Survey Meter. A scintillometer-type radioactivity detector using a photomultiplier tube with a circuit for combining pulses from the anode and from the dynode nearest the anode.

U. S. No. 2,742,586. H. Friedman. Iss. 4/17/56. App. 4/18/52.

Multi-Section Geiger-Mueller Counter. A radiation detector having a series of cylindrical cathodes placed end to end with insulating partitions between them and common anode wire through all the sections or separate anodes connected to coincidence circuits.

U. S. No. 2,743,374. H. S. McCreary, Jr. Iss. 4/24/56. App. 4/29/53. Assign. U.S.A.

Circuit Stabilizer. A scintillation-type radioactivity detector in which the long decay time of the electrometer tube is reduced by a mechanical switch which connects a low resistance across the high output resistance.

SEISMIC PROSPECTING

U. S. No. 2,740,488. S. N. Heaps. Iss. 4/3/56. App. 5/8/52. Assign. Socony Mobil Oil Co., Inc.

Seismic Shear Wave Generator. A mechanical device for generating shear waves by allowing a heavy mass to horizontally strike a target anchored to the earth by supports aligned in the direction of shear vibration desired.

U. S. No. 2,740,489. J. E. White and S. N. Heaps. Iss. 4/3/56. App. 5/8/52. Assign. Socony Mobil Oil Co., Inc.

Shear Wave Seismic Exploration. A seismic shear-wave exploration system in which a mass is given a high velocity perpendicular to the line of detectors and the shock of suddenly stopping the mass is imparted to the ground and the resulting transverse earth vibration recorded by shear detectors.

U. S. No. 2,740,945. E. T. Howes. Iss. 4/3/56. App. 7/6/53. Assign. United Geophysical Corp.

Seismic Prospecting System. A seismic recording system using a pressure detector and a velocity detector at the same location and separately recording or combining their outputs so that the direction of the wave can be determined.

U. S. No. 2,740,946. R. H. J. Geneslay. Iss. 4/3/56. App. 12/16/52 and 11/17/53. Assign. Compagnie Generale de Geophysique.

Seismometer. A variable-area reluctance-type seismometer having a suspended permanent magnet and coils embedded in the stationary pole pieces.

U. S. No. 2,741,754. H. B. Miller. Iss. 4/10/56. App. 12/27/50. Assign. Clevite Corp.

Disk Transducer. A hydrophone having a disk of barium titanate having an electrically-induced mechanical resonance across one diameter which is coupled to thickness changes by Poisson's ratio and which is excited at near resonance with the edges and one face of the disk acoustically shielded.

U. S. No. 2,742,779. S. Stein. Iss. 4/24/56. App. 1/23/52.

Differential Pendulum Vibrograph. A mechanically-recording differential vibrometer having two pendulums of different periods actuating a pen arm at different distances from pen-arm hinge and with the pen located on the common axis of the pendulums.

U. S. No. 2,743,785. F. W. Lee. Iss. 5/1/56. App. 8/20/51.

Apparatus for Making Seismic Surveys. A seismic recording system in which the record is electrically marked and using a transformer with two saturating windings, current in one winding being controlled by a gas triode which fires at the shot moment and the other winding controlled by a gas triode which fires upon reception of the seismic signal at the geophone.

U. S. No. 2,745,085. M. D. McCarty and K. W. McLoad. Iss. 5/8/56. App. 7/9/53. Assign. Socony Mobil Oil Co., Inc.,

Seismic Detector. A suspended-coil electromagnetic seismometer also having a stationary humbucking coil around the magnet connected in series opposition with the moving coil.

U. S. No. 2,745,507. A. G. Bodine, Jr. Iss. 5/15/56. App. 3/19/51.

Geophysical Transducer. Apparatus for generating beamed pulses of continuous wave seismic energy using three vibration generators coupled to the earth and driven at the same frequency but

having adjustable phase so that the direction of the resultant beam can be controlled and having a magnetic clutch between the driving motor and the generator so that the pulse length can be controlled.

U. S. No. 2,746,027. J. J. Murray. Iss. 5/15/56. App. 11/16/51.

Flux-Gap Variation Transducer for Hydrophones, Microphones, and Accelerometers. An electromechanical transducer having a permanent magnet with wedge-shaped pole faces and a suspension of magnetic material (such as powdered nickel) in a non-magnetic vehicle (such as rubber) in the space between the edges of the pole pieces.

U. S. No. 2,747,028. C. M. Clark. Iss. 5/22/56. App. 10/29/52. Assign. California Research Corp.

Amplifier Circuit. A gain control circuit for a seismograph amplifier using push-pull triodes operating in the microampere region so that the gain is an exponential function of the bias voltage obtained from an expander or avc.

U. S. No. 2,747,172. J. F. Bayhi. Iss. 5/22/56. App. 11/12/54. Assign. Esso Research and Engineering Co.

Geophone Arrangement for Seismic Prospecting. A geophone spread in which each location has an array with a number of geophones at the center and a smaller number at each side.

U. S. No. 2,748,348. E. R. McCarter. Iss. 5/29/56. App. 5/7/52. Assign. Esso Research and Engineering Co.

Testing Geophone Performance. A circuit which repeatedly applies a short pulse to the geophone to displace the coil and permits the geophone voltage subsequent to each pulse to be observed on an oscilloscope.

U. S. No. 2,748,370. R. W. Baltosser. Iss. 5/29/56. App. 6/26/51. Assign. Seismograph Service Corp.

Seismometer. A moving coil electromagnetic seismometer having magnet, pole pieces, and suspension springs arranged as a stack and clamped together in the case by a stiff spring.

WELL LOGGING

U. S. No. 2,740,695. S. E. Buckley and W. D. Mounce. Iss. 4/3/56. App. 12/17/54. Assign. Esso Research and Engineering Co.

Method for Logging Wells. A well logging method in which the filter cake is removed and the formation contacted with an oxidizing agent which reacts explosively with hydrocarbons and the resulting shock wave detected.

U. S. No. 2,740,898. A. H. Youmans. Iss. 4/3/56. App. 8/23/51. Assign. Well Surveys, Inc.

Method and Apparatus for Detecting Neutrons in the Presence of Other Radiation. A neutron logging detector in which a neutron capture reaction is used and separate pulses from coincident radiations caused by the reaction counted with a coincidence counter.

U. S. No. 2,741,705. A. S. McKay. Iss. 4/10/56. App. 1/30/51. Assign. The Texas Co.

Radioactive Well Logging. A neutron-neutron logging system having a neutron source and a neutron detector relatively close to the source and another neutron detector farther from the source, the measured neutron intensities being compared.

U. S. No. 2,741,916. B. F. Wiley and E. L. Clark. Iss. 4/17/56. App. 4/6/53.

Flowmeter. A subsurface flowmeter having two conduits connecting the spaces above and below a baffle, one conduit having a flow detector which controls a servo to adjust the speed of a motor-driven impeller in the other conduit, the speed of the impeller being indicated.

U. S. No. 2,741,917. R. G. Piety and B. F. Wiley. Iss. 4/17/56. App. 10/13/52. Assign. Phillips Petroleum Co.

Flowmeter. A subsurface flowmeter having two conduits connecting the spaces above and below a baffle, one conduit having a flow detector and the other conduit having a motor driven impeller with an electric contactor whose current pulses are integrated and indicated, the impeller rate being adjusted to give no flow in the first conduit.

U. S. No. 2,742,605. F. L. McMillan, Jr. Iss. 4/17/56. App. 12/27/49. Assign. Phillips Petroleum Co.

Coupling Circuit. A multi-channel electric well logging system using a rotating switch in the sonde to mix electrode signals so as to permit recording logs of various electrode spacings.

U. S. No. 2,742,606. L. D. Wann. Iss. 4/17/56. App. 10/25/54. Assign. Continental Oil Co.

Electrical Logging Apparatus. An electrode system for electric logging having guides which bear against the borehole wall and are connected by a linkage to the electrodes arranged so that outward motion of the guides moves the electrodes farther apart to automatically correct the log for variations in borehole diameter.

U. S. No. 2,742,629. G. C. Summers and R. A. Broding. Iss. 4/17/56. App. 1/11/52. Assign. Socony Mobil Oil Co., Inc.

Metallic Coupling Means for Acoustic Logging. A resilient device for mechanically connecting two spaced transducers of an acoustic logging apparatus having a rod inside a tube to form a tension-compression member or a spiral or convoluted member embedded in a solid rubber jacket whose outside diameter is the same as that of the transducers.

U. S. No. 2,743,414. M. C. Ferre. Iss. 4/24/56. App. 5/27/52. Assign. Schlumberger Well Surveying Corp.

Methods and Means for Preventing Deterioration of Electrodes in Measuring Systems Utilizing Unidirectional Electrical Signals. An electric logging method using square-wave current and measuring the potential only during the period in which current flow is opposite to naturally-occurring currents

U. S. No. 2,745,970. J. T. Dewan. Iss. 5/15/56. App. 1/4/52. Assign. Schlumberger Well Surveying Corp.

Radioactivity Detector. A detector for discriminating between radiations of different energy having an ionization chamber in a coaxial magnetic field and with negative screen located between the anode and cathode.

U. S. No. 2,746,009. G. H. McLaughlin and W. A. Robinson. Iss. 5/15/56. App. 12/24/51. Assign. The McPhar Engineering Co. of Canada Ltd.

Electromagnetic Drill Hole Exploration Method and Apparatus. An electromagnetic prospecting system in which an a-c field is generated by a vertical primary coil at the surface and picked up by a horizontal coil in a drill hole, the out-of-phase component of the pick-up voltage being compensated by adjusting the direction of an auxiliary coil on the surface connected in parallel with the primary coil.

U. S. No. 2,746,162. M. F. B. Picard. Iss. 5/22/56. App. 8/29/53 and 8/12/54. Assign. Societe de Prospection Electrique Procedes Schlumberger.

Apparatus for Determining the Deviation of a Borehole from the Vertical Axis. A surface-indicating well-surveying apparatus having a magnetic compass and an axially-pivoted cylinder with eccentric weight, each being arranged to actuate a rheostat and with a vibrator in the apparatus to prevent sticking of the moving elements.

U. S. No. 2,747,099. T. J. Nowak. Iss. 5/22/56. App. 1/29/53. Assign. Union Oil Co. of Calif.

Well Bore Logging. A logging method in which a radioactive solution miscible with one of the formation fluids and immiscible with others is forced into the formations, the formation fluids then allowed to flow into the well bore and a radioactivity log run, formations producing miscible fluid showing less intensity than those producing immiscible fluid.

U. S. No. 2,747,100. M. R. J. Wyllie and C. W. Tittle. Iss. 5/22/56. App. 9/19/52. Assign. Gulf Research & Development Co.

Method and Apparatus for Displacing Well Fuid With a Fluid Having Smaller Neutron Attenuation Characteristics. A neutron logging sonde in which the detector is surrounded by a flexible mercury-filled radially-expanding sleeve having a central channel to by-pass well fluid.

U. S. No. 2,747,294. A. B. Hildebrandt and F. H. Deily. Iss. 5/29/56. App. 5/26/53. Assign. Esso Research and Engineering Co.

Borehole Inclinometer. A well surveying apparatus which is placed in the drill string and has a mud by-pass, with the pressure differential of mud flowing through the by-pass actuating pistons which release a pendulum and magnetic compass and clamp them when mud circulation is stopped.

U. S. No. 2,747,401. H.-G. Doll. Iss. 5/29/56. App. 5/13/52. Assign. Schlumberger Well Surveying Corp.

Methods and Apparatus for Determining Hydraulic Characteristics of Formations Traversed by a Borehole. A device for determining the permeability of formations and having two or more tubular probes which are forced into the formation and through which a measured quantity of fluid can be flowed and the pressure differential measured.

U. S. No. 2,747,402. H.-G. Doll. Iss. 5/29/56. App. 9/27/51. Assign. Schlumberger Well Surveying Corp.

Differential Pressure Well Logging. A formation-pressure logging device having a pad which is pressed against the formation to isolate it and connects the formation to a pressure gage which measures the differential pressure between the formation and the well fluid by the electro-filtration potential set up by an electrolyte in the gage flowing through a porous plug.

U. S. No. 2,747,405. G. B. Thomas and J. Moon. Iss. 5/29/56. App. 10/10/51. Assign. Signal Oil and Gas Co.

Sub-Surface Bore Hole Gages. A device for recording well temperature and pressure and in which the chart is resiliently suspended so that depth marks are made on the chart by the stylus when the instrument is jarred.

MISCELLANEOUS

U. S. No. 2,740,291. J. B. Brown. Iss. 4/3/56. App. 10/8/51. Assign. Addeco, Inc.

Device for Obtaining Samples of Formation Cuttings Entrained in Drilling Fluids. A device which automatically samples cuttings in the mud return by catching the cuttings in a bucket, washing and draining the samples and dumping them into a container, and also records desired characteristics of the mud or drilling operation.

U. S. No. 2,740,292. B. E. Sewell. Iss. 4/3/56. App. 3/6/52. Assign. Esso Research and Engineering Co.

Apparatus for Logging Well Cuttings During Drilling. A method of logging the hardness of well cuttings by passing the mud returns through a roller-type crusher and recording the crusher vibrations, or passing the mud returns through a chamber with tortuous plates and recording the sound of the cuttings striking the plates.

U. S. No. 2,745,057. B. J. Dotson. Iss. 5/8/56. App. 8/2/52. Assign. Socony Mobil Oil Co., Inc.

Apparatus Used in Measuring Interstitial Water Content and Electrical Resistivity of Unmounted Core Samples. A cell for holding a core sample into which measured amounts of brine may be injected and having electrodes which contact membranes at the ends of the core and insulated pointed electrodes which contact the sides of the core.

U. S. No. 2,745,282. R. W. Rochon. Iss. 5/15/56. App. 3/2/53. Assign. Monarch Logging Co., Inc.

Gas Logging of Wells. A method of measuring the gas-releasing property of a drilling fluid by introducing a known amount of gas in a portion of the fluid, circulating through a gas-free well, and measuring the quantity of gas released when the fluid returns to the surface.

U. S. No. 2,746,034. A. F. Hasbrook. Iss. 5/15/56. App. 6/1/51. Assign. Olive S. Petty.

Positioning Determining System. A radio method of determining at a base point the distance between two remote points each having a transponder by measuring the travel time of a signal from the base to the first point and return, and also measuring the travel time of a signal from the base to the first point thence to the second point and return via the first point.

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2,740,292[a]	252	2,741,316	48	2,742,227	68
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2,741,125	200	2,741,917[a]	148	2,742,786	460
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* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

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REVIEWS COMMITTEE

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Acoustic and Other Physical Properties of Shallow-Water Sediments Off San Diego, E. L. Hamilton, George Shumway, H. W. Menard, and C. J. Shipek, Journal of the Acoustical Society of America, Vol. 28, Jan. 1956, pp. 1–15.

Low Sound Velocities in High-Porosity Sediments, Edwin L. Hamilton, Journal of the Acoustical Society of America, Vol. 28, Jan. 1956, pp. 16–19.

A geophysicist studying the propagation of elastic waves through the earth knows something about his medium. Investigations of the physical properties of rocks have been made at a number of laboratories. The information is not complete but neither is it non-existent. When the medium is not rock but water covered mud over rock, the situation is quite different. In spite of extensive seismic exploration of shallow water areas, very little has been published on their physical characteristics. Without knowledge of the medium properties, theoretical explanations of observed phenomena are impossible.

The publication, by the U. S. Navy Electronics Laboratory group, of acoustic and other physical properties of marine sediments is therefore a timely one. Thirty-five stations were occupied off San Diego. For most of these stations the following properties are tabulated: sediment type, density, median grain diameter, porosity, composition, sound velocity, acoustic impedance, reflection loss for normal incidence, and attenuation coefficient. A formidable list indeed! Sound velocities were measured both in situ, using ultrasonic probes, and by a resonant chamber method. Agreement between the sets of measurements is satisfactory.

Probably of most interest to exploration geophysicists are experimental curves relating particle diameter and sound velocity, porosity and sound velocity, and density and sound velocity. The NEL group suggests that after the mineral constituents of a sediment are known, a graph can be drawn for the linear inverse relationship between density and porosity. From the other curves and graphs for a similar sediment, approximate values of the velocity, impedance, and reflection loss at normal incidence can be picked.

Although the published material is extensive, for at least two reasons its usefulness in conventional seismic work is not clear. First, the bottom section examined was limited to the first foot. At normal seismic frequencies this represents a negligible fraction of a wavelength. Second, both the ultra-

sonic probing frequency (100 kcps) and resonant chamber frequencies (25–42 kcps) were far higher than those used in exploration. It is unlikely that the measured properties are independent of frequency. The work of Officer (Officer, 1955) relating acoustic velocity in soft bottoms and frequency is ignored.

The paper by Hamilton suffers from the same defect. At three stations bottom velocities lower than that of the water were observed. In fitting the data, Hamilton uses what is essentially a frequency independent equation for velocity. To Dr. Hamilton's credit, computed and measured values agree.

Finally, the reviewer would like to make a personal protest. The reflection loss at normal incidence is given in db. Those of us who are not engineers indulge those who are by translating db into amplitude ratios. It is annoying but easy. On the other hand, to find data that is calculated as amplitude ratios tabulated in db is an insult. Multiplication is really no harder than addition.

FRANKLYN K. LEVIN

REFERENCE

Officer, C. B., 1955, A Deep-Sea Seismic Reflection Profile: Geophysics, Vol. 20, pp. 270–282.

Geology and Ourselves. F. H. Edmonds, Philosophical Library, New York City, 1956, 256 pp.: $10.00.

In spite of its intriguing title, this British book will interest only a limited number of American readers, and these will be discouraged from purchasing it because of its unreasonably high price. It is hoped the British edition is more realistically priced; if not, there will be but few copies sold.

The author, F. H. Edmunds, has been a member of the staff of the Geological Survey of Great Britain for over 30 years so he writes from a wealth of experience in a limited area. His purpose in writing the book was to answer two questions commonly asked by laymen: "What does a geologist do?", and "What is the economic value of geology?". His objective is very much worthwhile but, as previously indicated, his answers will hardly satisfy an American reader.

Approximately one-half of the book is in the nature of an introduction to geology. It is interestingly written and well illustrated with pictures and diagrams. The author does, however, try to cover too wide a field in too few pages. Some minor topics could have been omitted in order to devote more space to the more important ones. Nevertheless, were this portion of the book to be bound separately and sold for a dollar or so, this reviewer could recommend it for its intended purpose. The author discusses clearly and briefly the historical background of our present geological knowledge, the history of the earth, the geological time scale, rocks, minerals, and fossils; and gives an explanation of geological maps and the technique of making them. In discussing the geological time scale and the corresponding Systems, representative sections found in Great Britain are described. Since Great Britain contains members of all Systems from the PreCambrian to the Recent, this is an eminently suitable procedure. The American reader will be reminded that the names of nearly all the geological Periods are of British origin.

The second half of the book discusses the economic value of geology but the discussion is limited strictly to the work of the geologist in the British Isles. Although there is a mention made of oil and gas; most of the space is devoted to the contribution made by geologists to the solution of problems connected with coal mining, civil engineering, water supply, and the exploitation of minerals and building materials. This type of work is, of course, of great local importance, but by confining himself so closely, the author does not give the reader a fair idea of the tremendous value of geological and geophysical techniques when applied to the world-wide exploration for new sources of raw materials hidden in the Mother Earth.

In addition to its high price, the book has several other faults. The Index, although labeled as such, is no index of subject matter, listing only names of people and places. Also, it is surprising to find not a single reference to other popular books on geology or to elementary texts. Since the book is purportedly written for laymen interested in the subject, some guide to further reading should be supplied.

W. T. BORN

Geophysics as a Career. Anonymous, Shell Petroleum Company, Ltd. London, 1956.

In Great Britain, as in the United States, there is a need for means of acquainting young men with the geophysical profession. The Shell Petroleum Co., Ltd., has helped meet this need by the publication of a beautifully illustrated brochure for distribution in England to science students in the age bracket 17 to 19 years. It is very similar in aim and scope to the S.E.G. brochure "Careers in Exploration Geophysics" published in 1953. Very probably, the success of the S.E.G. brochure was a factor influencing the publication of the English booklet.

It is interesting to compare the two booklets since they are very similar and yet quite different. Because of the difference in educational systems, boys are academically further advanced in England than those of the same age in this country. The Shell brochure could therefore be written for a more specialized group; those boys who have already decided to follow a scientific career. Both booklet describe the various geophysical methods, but the Shell brochure does so in much more detail and in text book fashion. The S.E.C. booklet makes free use of graphic arts in its presentation of facts, whereas the English booklet obtains its "eye appeal" from beautiful typography and numerous full page photographs of geophysical operations all over the world. Since but few geophysicists are locally employed in Great Britain, the Shell booklet quite properly emphasizes the fact that a career in exploration geophysics may lead one to the jungles of Borneo or the muskeg of Canada. Both booklets point out that a fondness for travel and the ability to undergo hardship are a primary qualification for an exploration geophysicist and agree quite well in their recommendations for academic preparation.

W. T. Born

History of Concepts of Gulf Coast Salt Dome Formation, L. L. Nettleton, Bulletin of the American Association of Petroleum Geologists, Vol. 39, No. 12, December, 1955, pp. 2373–2383. Model Studies of Salt Dome Tectonics, Travis J. Parker and A. N. McDowell, ibid, pp. 2383–2470.

Older readers of Geophysics will recall the great interest displayed by geologists and geophysicists when, in 1934, L. L. Nettleton first demonstrated his salt dome model at a meeting of the A.A.P.G. Using viscous liquids of two different densities, to represent salt overlain by sediments of greater density, he demonstrated that a slight deformation of the underlying liquid caused domelike structures to rise under the influence of gravitational forces alone. As a dome rose, a basinlike depression was formed around it which Nettleton called a "peripheral sink." Although this early model was not a true scale model of the salt and sediments of the Gulf Coast, Nettleton's demonstration did much to gain general acceptance of the hypothesis that the salt domes of the Gulf Coast were produced by the plastic flow of salt from a layer underlying heavier sediments, under the influence of gravitational forces, rather than by orogenic movement. The development of the peripheral sink in the model gave a suggestion of the cause of the rim synclines already mapped around some Texas salt domes.

In 1937 M. King Hubbert published a very important paper in the Bulletin of the Geological Society of America in which he discussed the theory of scale models as applied to the study of geological structures. He showed that, in order to simulate earth strata in small scale geological models, the materials used must be extremely weak; in fact, very soft muds, or even liquids, had mechanical properties of the correct order of magnitude. A detailed analysis of Nettleton's fluid model was made by M. B. Dobrin and published in the Transactions of the American Geophysical Union in 1941. Dobrin's work indicated that Nettleton's model had a scale factor of about one inch to the mile and so was at least an approximation to a true scale model. However, fluid models cannot show the faulting so commonly found in the sediments above salt domes. To do so, the overlying sediments must be simulated by some material having a very small but definite shear strength. Nettleton and Elkins did a limited amount of work using thin layers of granular materials over a viscous fluid and published preliminary report in 1947. These models demonstrated one additional significant phenomena—the cessation of dome growth when the overburden exceeded a critical thickness.

Nettleton's present paper reviews the early theories of salt dome formation and the model studies made by himself and by other workers in the field. The paper thus serves as an introduction to the

paper by Parker and McDowell which is a detailed account of their model studies made at Texas A. & M. College over a period of years. These studies were supported by the Engineering Experiment Station and a grant-in-aid from the A.A.P.G.

The work at Texas A. & M. was inspired by Nettleton's previous work and has resulted in a very considerable advance in the application of model studies to geological structure problems. The authors constructed some 800 different models of various materials in an effort to build true scale models. The granular materials suggested by Nettleton were investigated and useful qualitative results obtained. However, it was found that the closest practical approach to a true scale model was obtained by using asphalt to represent salt, and very weak muds to represent the overlying materials; the models having lateral dimensions of a few feet. The muds were formed by pouring a slurry of mud over a layer of asphalt and allowing the solid particles to settle to form the overlying later. Random settling of the mud particles resulted in differential pressures upon the asphalt sufficient to cause noticeable movement within 24 hours without the application of other forces. Domes could be produced in a variety of ways. Variations in overburden thickness, lateral variations in overburden density, and deformation of the model by external applied force all caused domes to rise. As asphalt flowed into a rising dome, a peripheral sink was produced in the asphalt which, in turn, sometimes caused the initiation of a number of secondary domes around the margins of the sink. Usually the diameter of the sink was some six to eight times the diameter of the primary dome.

It was found that movement of a dome stopped when the overburden thickness exceeded a critical value, thus confirming the earlier observation of Nettleton. It was also observed that the diameter of the domes formed were related to the thickness of the asphalt layer from which they arose, the diameters of the domes being approximately equal to the thickness of the original layer. This observation suggests that the source of the salt forming Gulf Coast salt domes is thousands of feet, rather than a few hundred feet thick.

The use of mud of finite shear strength permitted faults to develop above a growing dome. Radial faults were numerous, and grabens sometimes developed as the result of the greater uplift of marginal fault segments. In general, the fault patterns observed were not unlike those observed over actual salt domes.

Parker and McDowell are to be commended for a very fine exposition of a difficult and tedious experimental project. Their paper not only describes their experimental work and results, by word and by pictures, but gives also an excellent summary of the existing geological knowledge of salt domes; discusses all theories proposed for their origin; gives a resume of Hubbert's work on theory of scale models; and concludes with a very sound critical discussion of their own work and its application to the salt dome problem. In the latter they emphasize that geological models true to scale in every respect generally cannot be built. Usually insufficient data are available concerning the pertinent physical properties of the earth structures being modeled and only crude estimates are available for the time intervals involved in tectonic movements. Added to this uncertainty is the almost impossible task of finding suitable materials of which to make the models. Application of the results when obtained from model experiments to interpretation of geological field observations must be cautiously done and the lack of accuracy in scale factors must always be kept in mind.

This reviewer feels that all the workers whose work is here mentioned have contributed greatly to geological thought by clarifying the physical principles involved in tectonic movements. It is unfortunate, but very true, that much of the model work done by geologists was, until very recently, done with seeming disregard of elementary physical principles. Dr. Nettleton closes his paper with a statement regarding model work, saying, "Further progress will depend upon careful considerations of quantitative and analytical factors, and not on intuitional models which produce artificial structures which merely look good because the results give forms or deformations which appear similar to those in nature." Amen!

W. T. BORN

Propagation of Sound Pulses in a Dispersive Medium, J. M. Proud, P. Tamarkin, and E. T. Kornhauser. The Journal of the Acoustical Society of America, Vol. 8, January, 1956, pp. 80–85.

During recent years a number of laboratories, industrial and academic, have experimented with pulse propagation analogue computers, i.e., models. Professor Tamarkin's group at Brown University has now entered the field. The model described in this paper is of less immediate interest than several others discussed in GEOPHYSICS—neither the pulse shape nor frequency absorption law have immediate analogues in normal seismic work. Nonetheless, as a confirmation of simple propagation theory with dispersion, the work is enlightening.

The model considered by the Brown group is a water filled rectangular wave guide with pressure-release sides. The input is a long rectangular pulse containing carrier frequency. Except for variations at the start of the detected pulse, the agreement between experimental forms and the ones derived from a theory of Pearson is excellent. Deviations from a zero rise time are assumed to cause the minor initial discrepancies.

We surely can expect further papers from Brown's Department of Physics. Having satisfied themselves that their model does indeed give agreement with theory in simple cases, Professor Tamarkin and his co-workers will doubtlessly move on to more complicated and interesting situations.

FRANKLYN K. LEVIN

PUBLICATIONS RECEIVED

American Journal of Science, v. 254, nos. 5, 6 & 7 (May, June & July, 1956)
Annales de Geophysique, v. 12, n. 1 (1956)
Bulletin of the Earthquake Research Institute, Supplementary Part (March, 1956)
Bulletin of the Institute of Nuclear Sciences (Belgrade), v. 6 (March, 1956)
Bulletin of the Research Council of Israel, v. 5B, n. 2 (December, 1955)
Bulletin of the Seismological Society of America, v. 46, n. 2 (April, 1956)
Butsuri-Tanko, v. 9, n. 1 (1956)
Canadian Geophysical Bulletin, v. 8 (December, 1955)
Department of Mines South Australia, Geological Survey, *Report of Investigations for 1955*, nos. 2, 5 & 6
Deutsche Hydrographische Zeitschrift, v. 8, nos. 5 & 6 (1955)
Economic Geology, v. 51, nos. 3 & 4 (May & June-July, 1956)
Erdol und Kohle, v. 9, nos. 3, 4, 5 & 6 (March, April, May & June, 1956)
Geofizikai Kozlemenyek, v. 5, n. 1 (1955)
Geological Abstracts, v. 4, n. 2 (June, 1956)
Geophysical Abstracts, v. 164 (January–March, 1956)
Geophysical Notes, v. 8, n. 2 (1955)
Geophysical Prospecting, v. 4, n. 2 (June, 1956)
Journal Academy Science USSR, Series Geophysical, 1956, nos. 1–5
Journal of Geophysical Research, v. 61, n. 2 (in 2 parts) (June, 1956)
Journal of Petroleum Technology, v. 8, n. 4 (April, 1956)
Journal of the University of Moscow, 1956, nos. 2 & 3
Meteoros, v. 5, n. 4 (October–December, 1955)
Mineral Wealth of Greece, v. 3 (1953)
Mining Engineering, v. 8, nos. 4, 5, 6 & 7 (April, May, June & July, 1956)
Petroleum Economy (USSR), 1956, nos. 3, 4 & 5
Quarterly Journal of the Geological Society of London, v. 111, n. 444 (March 2, 1956)
Review of Scientific Instruments, v. 27, nos. 4, 6 & 7 (April, June & July, 1956)
Revista di Geofisica Applicata, v. 16, n. 1–2 (1955)
Science, v. 123, nos. 3198–3209 (April 13 through June 29, 1956); v. 124, nos. 3210–3213 (July 6 through July 31, 1956)
Science Reports of The Tohoku University, v. 7, n. 3 and supplement (March, 1956)
Scientific Monthly, v. 82, nos 5 & 6 (May & June, 1956); v. 83, nos. 1 & 2 (July & August, 1956)
Soviet Physics JETP, v. 2, nos. 2 & 3 (March & May, 1956)
Tellus, v. 8, nos. 1 & 2 (February & May, 1956)
Transactions American Geophysical Union, v. 37, nos. 2 & 3 (April & June, 1956)

CONTRIBUTORS

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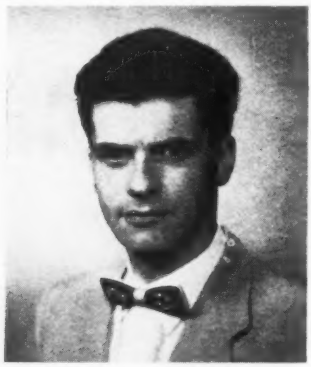
W. BAILLIE is a graduate in geology from the University of Saskatchewan. He spent two field seasons with the Geological Survey of Canada prior to entering oil exploration work in 1940 with the Tropical Oil Company in South America. He later joined Shell Oil Company and served as party chief in Mississippi; division geophysicist in Jackson, Mississippi; geophysical supervisor in New Brunswick; and division geophysicist in Calgary, Alberta. He resigned from Shell Oil Company to assume his present position as Vice President of Frontier Geophysical Ltd.

SYDNEY P. CLARK, JR.

SYDNEY P. CLARK, JR. received the Ph.D. in geophysics from Harvard University in 1955. He has been a Research Fellow in geophysics at Harvard since then, and has been engaged in the synthesis of minerals at high temperatures and pressures and in geothermal studies.



BERNARD GRUNEBAUM

BERNARD GRUNEBAUM received diplomas in Higher Mathematics (1944), Civil Engineering (1946) and Electrical Engineering (1946) from Catholic University of Santiago, Chile. He received further academic training with the United States Coast and Geodetic Survey under the Point Four International Cooperation Program in the field of gravity and geomagnetism, having received a pertinent degree in 1953. During 1954 he performed research work under the direction of E. G. Kogbetliantz, of International Business Machines Corp., in the field of applications of potential theory to geophysical interpretation. He was assistant professor of mathematics at Catholic University of Santiago in 1944 and 1945; professor of mathematical physics at Chilean Military Academy, technical division from 1944 to 1946; and geophysicist of the Chilean government owned oil company (ENAP) from 1947 to 1955. Since 1955 he has been research mathematician for McCollum Exploration Company, Houston, Texas.

Mr. Grunebaum is a member of the Society of Exploration Geophysicists.

V. L. "VIC" JONES

V. L. "VIC" JONES received his A.B. and M.S. degrees from the University of Oklahoma in 1925–27, with majors in physics and mathematics. He did further graduate work at the universities of Colorado and Oklahoma where he held instructorships in physics in 1927–28 and 1931–32 respectively. He was employed by Geophysical Research Corp. on the first commercial reflection seismograph crew in Oklahoma during the summer of 1927, where he alternated as observer and computor. He was later Head of the Dept. of Geophysics at The University of Tulsa (1946–51), where he organized and sponsored the first Student Section of SEG. Vic was one of the organizers and first officers of the first local section of SEG, the Geophysical Society of Tulsa, of which he is currently the Editor. He was Chairman of the SEG Student Membership Committee in 1948–49. He has been engaged in geophysical research and interpretation analysis with various companies among which are: Amerada Petroleum Corp., Stanolind Oil & Gas Co., Barnsdall Oil Co., Frost Geophysical Corp., and Geophysical Development Corp.

Vic entered the consulting field in 1940, and is currently an independent geophysicist. In January of 1955 he set up his own geophysical contract organization, Terrametric Exploration Co. For the past twelve years he has specialized in gravity and magnetic instrumentation, procedures and interpretation techniques for detecting structures associated with igneous intrusives in central and northeastern Oklahoma, and central and southeastern Kansas. He has recently completed a research project—geophysical and geological investigations of the Owasso dome structure in Tulsa County, on which he gave a paper before the Annual Meeting of SEG at St. Louis in April of 1951.

Mr. Jones is a member of the American Geophysical Union, Seismological Society of America, The Geochemical Society, European Association of Exploration Geophysicists, Tulsa Geological Society, Tulsa Astronomical Society (Pres. 1941), Sigma Xi, Sigma Pi Sigma, Alpha Sigma Delta and Society of Exploration Geophysicists.

J. S. OSOBA received his B.A. degree from the University of Texas and Ph.D. in physics from Washington University in 1949. Since that time he has been with the Production Research Division of the Humble Oil & Refining Company in Houston, Texas.

J. S. OSOBA

FREDERICK M. PERKINS, JR.

FREDERICK M. PERKINS, JR., received his B.S. and M.S. degrees in chemical engineering at the University of Florida in 1952. Since that time he has been with the Production Research Division of Humble Oil & Refining Company in Houston, Texas.

KENNETH H. RIBE received his B.S. and M.A. degrees in physics from the University of Texas. He joined the Production Research Division of Humble Oil & Refining Company in 1952.

KENNETH H. RIBE

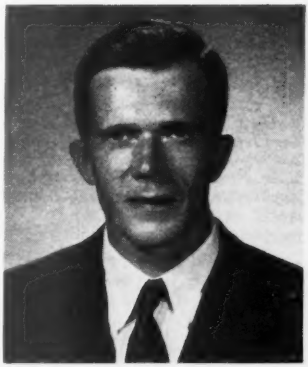
V. BHASKARA RAO

V. BHASKARA RAO was born in Kevvur, Andhra State, India in 1928. He received his B.Sc. (Honours) degree in Physics and M.Sc. degree in Applied Geophysics from the Andhra University, Waltair, in 1949 and 1950. From 1950 to 1953, he was a Research Fellow in the Geophysics Department of the Andhra University. Under the Colombo Plan, he was with the Department of Geology and Geophysics of the Sydney University, Australia, till 1955, for his Ph.D. degree. He is at present on the staff of the Andhra University as Lecturer in Geophysics.

Mr. Bhaskara Rao is a member of the Society of Exploration Geophysicists and the American Geophysical Union.

T. ROZSA is a graduate geological engineer from Michigan College of Mining and Technology. He was employed by Shell Oil Company as junior seismologist in 1936 and served in various capacities during his career with Shell including: party chief in Oklahoma, Texas, Illinois and Michigan; division geophysicist in Jackson, Mississippi and Baton Rouge, Louisiana; and finally area geophysicist in Calgary, Alberta. He resigned from Shell Oil Company to organize Frontier Geophysical Limited.

T. ROZSA



DONALD W. SMELLIE

DONALD W. SMELLIE was born in Ottawa, Ontario, in 1927 and received elementary and high school education there. He graduated with a Bachelor of Science degree in Physics from Queen's University in 1950 and a Master of Applied Science in Engineering Physics from University of British Columbia in 1951. His summers had been spent with the National Research Council of Canada doing work in the Acoustics Laboratory and Nuclear Physics Branch. In 1951 and 1952 he was engaged in electromagnetic prospecting with Dominion Gulf Company, returning to the University of British Columbia in 1952 for further graduate work in Physics. In 1953 he went to the Australian National University as a Research Scholar and has conducted theoretical magnetic and experimental rock magnetism studies.

Mr. Smellie is a junior member of the Canadian Institute of Mining and Metallurgy, an Associate member of the Society of Exploration Geophysicists, a member of the European Association of Exploration Geophysicists and the New Zealand Alpine Club, and a life member of the Royal Astronomical Society of Canada.

Biographies and photographs of the following authors appear in recent issues of GEOPHYSICS: F. F Evison, v. 17, p. 980 (October, 1952); Irwin Roman, v. 11, p 564 (October, 1946) and v. 19, p. 155 (January, 1954).

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Treas.: John E. Bondurant
Editor: V. L. Jones
Secty.: Ralph D. Lynn
The Carter Oil Company
Box 801
Tulsa 2, Oklahoma
Meetings: Monthly, 2nd Thursday
7:00 P.M., meeting only
University of Tulsa, room 224,
Petroleum Science Hall

SEG Houston Section

Chartered February 14, 1948
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2nd V-Pres.: John Byers
Treas.: M. L. Benke
Secty.: S. Brooks Stewart
Sohio Petroleum Company
1964 West Gray
Houston 12, Texas
Meetings: Monthly
Noon luncheon ($1.65)
Rice Hotel

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Chartered April 12, 1948
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V-Pres. N.D.: Paul F. Clement
V-Pres. S.D.: Lawrence K. Morris
Secty.: Thomas A. Roy
The Ohio Oil Company
Box 193

Bakersfield, California
Meetings: Monthly, 2nd Thursday
Noon luncheon ($2.00)
Biltmore Hotel, Los Angeles

Dallas Geophysical Society

Chartered August 7, 1948
Pres.: John A. Lester
1st V-Pres.: Henry F. Dunlap
2nd V-Pres.: Glenn M. Conklin
Secty.: M. S. Hathaway
The Atlantic Refining Co.
Box 2819
Dallas, Texas
Meetings: Monthly, usually 2nd Monday
8:00 P.M.
Fondren Science Building
Southern Methodist University

Fort Worth Geophysical Society

Chartered August 7, 1948
Pres.: A. E. McKay
V-Pres.: R. C. Herron
Secty.: Carl Wert
Gulf Oil Corporation
Drawer 1290
Forth Worth, Texas
Meetings: Monthly, 4th Monday
Noon luncheon ($1.50)
Texas Hotel

Ark-La-Tex Geophysical Society

Chartered Marcrh 12, 1949
Pres.: Herbert J. Ferber
V-Pres.: Charles P. Bragg
Secty.: H. L. Grant
Western Geophysical Company
191 Atlantic Street
Shreveport, Louisiana
Meetings: Monthly, last Monday
Noon luncheon ($1.50)
Captain Shreve Hotel
Shreveport

Permian Basin Geophysical Society

Chartered January 30, 1950
Pres.: Decker Dawson
1st V-Pres.: Maxey Pinson
2nd V-Pres.: W. A. Seal, Jr.
Treas.: R. J. Knott
Stanolind Oil & Gas Company
Box 1540
Midland, Texas
Meetings: Monthly, 2nd Tuesday
7:30 P.M., free coffee & donuts
Midland Womens Club
Midland, Texas

Denver Geophysical Society

Chartered May 19, 1950
Pres.: E. B. Wasson
V-Pres.: C. E. Riddell
Secty.: R. R. Parks
The Chicago Corporation
333 Logan Street
Denver, Colorado
Meetings: Monthly, 1st Monday
5:30 P.M., meeting only
Petroleum Club, Denver

Canadian SEG

Chartered January 24, 1952
Pres.: Ralph B. Ross
V-Pres.: George J. Blundun
Secty.: Don V. Bigelow
Mobil Oil of Canada Ltd
Mobil Oil Building
Calgary, Alberta
Meetings: Monthly, no set schedule

Geophysical Society of Oklahoma City

Chartered September 30, 1952
Pres.: John Bemrose
1st V-Pres.: W. B. Robinson
2nd V-Pres.: D. D. Moore
Treas.: Ben W. Smith
Secty.: George E. Anderson
Stanolind Oil & Gas Co.
Box 1654
Oklahoma City, Oklahoma
Meetings: Monthly, 2nd or 3rd Monday
Time and place to be announced

Casper Geophysical Society

Chartered May 23, 1953
Pres.: W. N. Farmer
V-Pres.: H. F. Dodson
Secty.: C. M. Brown
Teton Tool Company

Box 338
Mills, Wyoming
Meetings: Monthly, 1st Monday
7:00 P.M., dinner ($2.75)
Townsend Hotel
Casper, Wyoming

Geophysical Society of South Texas

Chartered November 9, 1953
Pres.: W. Lee Moore
V-Pres.: William R. Gray
Secty.: Dillon S. Frazier
Petty Geophysical Engg. Co.
Transit Tower
San Antonio, Texas
Meetings: 1st and 3rd Wednesdays
Noon luncheon, Sommers Cafeteria
Main Plaza, San Antonio

Southeastern Geophysical Society

Chartered April 1, 1954
Pres.: John F. Boyd
V-Pres.: O. G. Holekamp
Secty.: R. E. Halsey
Sinclair Oil & Gas Co.
860 St. Charles Ave.
New Orleans, Louisiana
Meetings: Monthly, 3rd Monday
Noon luncheon ($1.50)
St. Charles Hotel
New Orleans

Montana Geophysical Society

Chartered April 12, 1954
Pres.: Sam Marsh
1st V-Pres.: Jack Peters
2nd V-Pres.: M. D. Wickerham
Secty.: C. F. Moore
Sohio Petroleum Company
Box 2558
Billings, Montana
Meetings: Monthly, 2nd Monday
7:30 P.M., Billings Petroleum Club
Billings, Montana

Jackson Geophysical Society

Chartered May 12, 1955
Pres.: Fred Forward
V-Pres.: W. J. Robinson
Secty.: R. Long
Stanolind Oil & Gas Co.
1166 Raymond Road
Jackson, Mississippi
Meetings: Monthly, during 3rd week
5:30 P.M., refreshments
6:30 P.M., dinner ($2.00)
Roof Garden of Robert E. Lee Hotel
Jackson, Mississippi

Southwest Louisiana Geophysical Society

Chartered January 4, 1956
Pres.: J. J. Schneider, Jr.
1st V-Pres.: E. L. Ricketts
2nd V-Pres.: E. L. Current
Secty.: J. W. Bell, Jr.
Pan-American Production Co.
Drawer 1409, Oil Center Station
Lafayette, Louisiana
Meetings: to be announced

Dakota Geophysical Society

To be chartered
Pres.: W. E. Phillips
1st V-Pres.: Hugh McCain
2nd V-Pres.: Quin Hayes
Secty.: R. R. Phair
Roundup Powder Company
Box 452
Bismarck, North Dakota
Meetings: Monthly, 1st Friday
7:30 P.M., Petroleum Club
Prince Hotel
Bismarck, North Dakota

* * *

STUDENT SOCIETIES

(Affiliated)

Colorado School of Mines Society of Student Geophysicists

Secty.: Robert I. Bucknell
Department of Geophysics
Colorado School of Mines
Golden, Colorado
Meetings: to be announced

Geophysical Society of Saint Louis University

Secty.: Thomas McEvilly
Saint Louis University
3621 Olive Street
St. Louis 8, Missouri
Meetings: Monthly, 2nd Wednesday
7:30 P.M., meeting only
Institute of Technology

SEG Houston Student Section

Secty.: D. H. Cook
University of Houston
Houston, Texas
Meetings: to be announced

University of Toronto Geophysical Society

Secty.: John E. Hogg
49 St. George Street
Toronto 5, Ontario
Meetings: Bi-weekly, alternate Thursdays
4:00 P.M., 49 St. George Street

University of Tulsa Student Geophysical Society

Secty.: Pat Doby
Department of Geophysics
600 South College
Tulsa, Oklahoma
Meetings: Weekly, Thursday
4:00 P.M., Petroleum Science Bldg.

Trans-Pecos Student Section

Secty.: John T. Sample, Jr.
Box 56
Texas Western College
El Paso, Texas
Meetings: to be announced

Pennsylvania State University Geophysical Society

Secty.: James B. Imswiler
College of Mineral Industries
University Park, Pa.
Meetings: to be announced

University of Utah Geophysical Society

Secty.: Howard L. Confer
College of Mines and
Mineral Industries
Salt Lake City 1, Utah
Meetings: Monthly, 1st Thursday
Noon, Mines Building
Other special meetings to be announced

Georgia Institute of Technology, Geophysical Society

Secty.: William Hogarth
Box 4748
Atlanta, Georgia
Meetings: to be announced

MEMBERSHIP APPLICATIONS RECEIVED

Applications for Active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the name of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the President within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

Harris H. Allen (A. J. Hintze, Paul Farren, G. A. Berg, R. P. Clark)
John C. Anderson (R. F. Bennett, R. D. Roberts, C. B. Smith, C. C. Sellers)
Klaus G. Anderson
W. L. Bailey (R. R. Rosenkrans, T. F. Dupont, W. S. Hawes, K. A. Webb)
V. S. Balderson (J. L. Morris, O. A. Strange, J. A. Adams, Dean Walling)
R. L. Brasell (R. A. Pohly, George Seeburger, R. B. Kerbow)
Randolph W. Bromery (Gordon Anderson, Roland G. Henderson, Elizabeth R. King)
R. K. Bryant (E. J. DiGiulio, R. D. DeJournette, Dupree McGrady, J. M. Desmond)
J. G. Bunker (H. C. Bickel, A. J. Barthelmes, Robert Baum)
John C. Butler (A. B. Bryan, C. N. Hurry, W. W. Clark, Bryan A. Duby)
J. Y. Chereau (Claude Aynard, A. Roger, Paul Giraud)
Verner L. Crackel (M. J. Hill, G. R. Bell, J. P. Gates, Paul Clements)
G. T. Crosby (John L. Bible, Joseph S. Pluta, G. L. Barksdale)
Lawson O. Dailey, Jr. (O. C. Clifford, Jr., C. H. Hightower, E. L. DeLoach M. S. Hathaway)
George F. Darrow (Hal R. Adams, Gordon Kirby, J. R. Willcockson, R. A. Fellows)
Harry R. Davis (G. N. Meade, G L. Ellis, H. A. Willis, W. H. Hawkes)
R. W. Edmund (R. F. Bennett, H. C. Talley, Jr., Paul Lyons, A. H. Bleyberg)
Louis W. Erath (R. R. Thompson, K. R. Beeman, R. H. Parker, D. P. Carlton)
H. L. Ernst, Jr. (R. W. Mossman, L. G. Morris, S. W. Fruehling, R. W. Saubert)
Roy R. Farnsworth (K. S. Cohick, E. M. Curry, J. G. Parker, J. C. Waterman)
William B. Farrington (A. L. Pierson, III, V. L. Redding, D. H. Gardner)
Robert C. Fitzpatrick (N. A. Haskell, D. L. Barnes, J. T. Wilson, G. P. Woolard)
Russell J. Ford (Stefan Von Croy, D. F. Smith, B. C. Timm, W. J. Slagle)
Harry E. Fritz (Sigmund Hammer, W. A. Meszaros, T. C. Wilson, H. L. Rase)
H. E. Gerhiser (J. D. Marr, F. F. Reynolds, A. A. Hunzicker, R. R. Rosenkrans)
Gordon A. Gibb E. Nash, J. A. Lester, R. M. Nugent)
P. Gottfredson (R. B. Ross, R. J. Copeland, H. J. McGrew, S. G. Pearson)
Lewis R. Graham (M. C. Kelsey, E. F. McMullin, Donald O. Acrey)
Robert D. Graves (W. Harlan Taylor, Albert Kimes, O. P. Gill, W. Scott Mather)
K. Grillowitzer (R. B. Ross. H. J. McGrew, R. J. Copeland, J. W. Bowden)
Otto Hackel (W. D. Cortright, T. P. Ellsworth, L. G. Snedden, W. L. Matjasic)
Charles K. Hager (E. M. Hall, Jr., D. D. Mize, J. P. Anthony)
B. W. Hamilton (A. S. Gibson, A. P. Crosby, C. J. Chapman)
M. T. Hanna (J. E. McGee, W. B. Lee, M. D. Butler, L. P. Bristley, Jr.)
L. L. Harp (G. P. Montgomery, F. H. McGowan, A. P. Wendler, D. P. Carlton)
Rayburn H. Haskins (Paul Tucker, F. L. Cady, George Walton, S. R. Marsh)
L. R. Hatlelid (G. C. Angew, C. H. Acheson, R. Pallet, U. J. Chaput)
P. J. Helsdingen (R. D. Terry, H. F. Sagoci, N. R. Park)
W. E. Hightower (W. B. Perry, H. M. Thralls, A. M. House)
Wade Hitchcock, Jr. (C. C. Mason, Jack Starr, H. C. Minturn)
J. Hodgkinson (E. F. K. Zarudski, J. C. Hoffmann, S. O. Patterson, E. L. Fetzer)

Jimmie R. Hughes (C. H. Carlisle, J. A. Smith, O. T. Halliday, H. C. Kriegel)
W. C. Inches (J. A. Lester, J. C. Eley, R. M. Nugent, W. E. Jackson)
John B. Jacobson (E. G. Dobrick, S. C. Stoneham, W. C. Mosier)
Robert L. Johnston (M. J. Hill, G. W. Ledingham, P. F. Clement, W. P. Gealy)
Claude Joie (Claude Aynard, Paul Giraud, Lucien Beaufort)
Martin C. Kane (L. C. Pakiser, D. R. Mabey, Irwin Roman, James Balsley)
E. E. Kasiske (W. R. Dortch, E. F. Helser, L. R. Tucker, P. P. Conrad)
Elzie A. Kee (A. J. Hintze, W. H. Courtier, J. C. Rollins, F. H. Morris)
W. J. Kirst, Jr. (V. E. Prestine, J. M. Desmond, Dupree McGrady, H. Johnson)
Lee C. Lamar (E. M. McNatt, P. L. Lyons, R. W. Gemmer, Gordon Kirby)
Thomas M. LaMonica (G. A. Grimm, J. R. Willcockson, W. H. Hawkes)
James V. Looney (C. C. Sellers, L. J. Larguier, C. F. Moore, Jr., R. F. Bennett)
Donald MacDonald (Geoffrey Bond, A. T. Cooper, W. H. Swift, F. J. McIntosh)
Paul E. Madeley (T. T. Pope, Burton McCollum, S. G. Ray, R. R. Pittman)
Ciro Maino (T. Rocco, C. Morelli, L. Solaini, M. A. Boccalery)
Anthony V. Mattos (L. K. Morris, J. D. Rookus, R. K. Gilbert, L. W. Louder)
A. S. McKay (B. D. Lee, G. Herzog, A. L. Parrack, O. B. Hocker)
Everett B. Miller (H. R. Prescott, A. L. Ladner, W. C. Kimball, G. A. Berg)
O. C. Montgomery (J. E. Bondurant, S. D. Elliott, H. C. Johnsen, F. C. Cullison)
Graham B. Moody (Phil P. Gaby, G. M. Cunningham, P. L. Lyons, C. H. Green)
E. James Moore (James T. Wilson, N. A. Haskell, B. F. Howell, Jr.)
J. Najera V. (G. J. Kohler, Jr., Jesus Basurto, J. W. Thomas, Daniel Gutierrez)
S. Oczkowski (R. D. Holland, H. R. Renden, J. Sosnowski, W. Smith)
Judd H. Oualline (W. M. Erdahl, W. G. Allen, Chester Sappington)
George F. Pappas (Paul Farren, V. G. Winston, A. G. Morton, H. L. Johnson)
J. M. Petit (P. Giraud, F. Blondy, C. Aynard)
Eric H. Phillips (M. J. Hill, G. R. Bell, J. P. Gates, J. C. Benzley)
F. Harvey Pless (H. L. Copeland, Peter Jacobsen, Jr, W. J. Pfeffer)
James Pollock (T. M. Broderick, A. S. Kromer, Paul Dashine, Harry Donald)
James R. Rae (E. J. Shimek, W. H. Reese, J. D. Sides, G. Hess)
G. Rampel (R J. Bily, A. P. Crosby, H. W. Stoneman)
George L. Robb (B. F. Rummerfield, N. J. Bentley-Lelwellyn, Dart Wantland)
J. E. Robinson (C. H. Acheson, A. P. Crosby, J. B. Murphy, H. R. Ellard)
Alton A. Rodgers (H. C. Kriegel, J. A. Smith, O. T. Halliday, R. H. Schmuck)
C. Rosoff (Paul Giraud, Claude Aynard, R. Geneslay)
F. J. Sachnil (O. B. Hocker, C. R. Wallace, D. T. McCreary, J. M. Kendall)
A. B. Sanders (W. E. Hollingsworth, R. H. Hopkins, H. C. Weston, J. W. Meek)
V. Schut (E. G. Haines, J. D. Hale, A. E. Pallister, F. H. v. Goor)
Marshall Shackelford (J. F. Rollins, R. V. Coleman, Jr., M. C. Kelsey)
E. J. Sharpe (A. A. Brant, Hans Lundberg, J. T. Wilson, C. F. Sellers)
Ernest K. Shaw (A. P. Crosby, A. S. Gibson, C. J. Chapman)
Marshall B. Smith (J. R. Walker, K. R. Beeman, Paul Farren)
William V. Snider (R. M. Davis, F. A. Roberts, George Walton, C. H. Quinn)
Joseph W. Spencer (F. G. Blake, Jr., W. W. Garvin, N. A. Riley, K. E. Burg)
Robert D. Sprague (R. F. Bennett, P. L. Lyons, E. W. Frowe, K. R. Wells)
Charles B. Stone (O. B. Manes, J. R. Randolph, A. B. Wood)
Ralph I. Steeves (R. W. Cowden, H. E. Stommel, C. C. Lister, J. A. Smith)
Glen H. Swenumson (H. E. Prokesh, E. L. Mount, D. S. Godshalk, L. E. Whitehead)
William F. Tanner, Jr. (John Norden, H. W. Straley III, Hamilton Johnson, R. H. Dott)
Henry A. Taylor (R. O. Smith, L. F. Guseman, W. W. Daly, C. V. Aderman)
Jack A. Taylor (R. N. Gsell, J. A. Lester, H. C. Cortes, Paul Nash)
Edwin L. Tomlin (G. G. McRoberts, W. W. Clark, R. F. Weichert, C. N. Hurry)

Daniel A. Valencio
Earl D. Van Reenan
George W. Watson (C. N. Hurry, M. Romberg, J. T. Williams, R. M. Davis)
R. H. Watson (F. B. Wallis, J. M. Smith, W. H. Smith)
Richard A. Whetherhead (E. F. Helser, Claude Aynard, J. B. McKee, P. P. Conrad)
John D. White (G. J. Shoup, R. D. DeJournette, F. J. DiGuilio)
Robert W. White (K. M. Lawrence, J. E. Owen, W. T. Born)
Donald E. Wilson (R. F. Bennett, R. D. Roberts, W. L. Hurt, C. C. Sellers)

APPLICATIONS FOR TRANSFER TO ACTIVE MEMBERSHIP

Douglas D. Barman (C. R. Wallace, D. J. Bratton, M. J. Rieger)
Kevin M. Barry (V. J. Blum, D. J. O'Donnell, W. B. Robinson)
John H. Bell (E. H. Shannon, L. W. Cobena, B. H. Treybig, Jr.)
L. K. Buller (G. J. Long, Sidon Harris, H. B. Peacock)
Albert J. Christman (C. C. Zimmerman, H. W McDonald, C. V. Aderman)
D. B. Cocovinis (R. L. Lay, O. B. Hocker, W. H. Gibson)
S. Norman Domenico (John C. Hollister, H. E. Stommel, W. B. Widess)
Robert H. Dunwoody (H. F. Patterson, K. C. Thompson, Roy B. Jamison)
Wesley N Farmer (J. W. Mathews, V. E. Prestine, Dupree McGrady)
T. A. Garrity, Jr. (Harvey Cooper, John Collier, John C. Hollister)
G. W. Green (J. N. Gragnon, J. B. Hazelrigg, Elwin Bennett)
L. L. Hammial (James M. Wilson. T. I. Harkins, O. D. Tatsch)
Charles A. Hassenfratz, Jr. (V. Robert Kerr, A. E. McKay, R. W. Dudley)
Ralph R. Hill (J. D. Marr, C. R. Dodd, W. W. Jameson, K. A. Webb)
Robert B. Hill (D. E. Mackey, Jackson Young, R. W. Carter)
Hubert B. Hunt (O. C. Clifford, Jr., C. H. Hightower, H. L. Cobb)
B. C. Jones (J. E. Stones, Frank Ittner, Cecil Reel)
Billy F. King (R. D. DeJournette, F. J. DiGiulio, Merrill Smith)
Joseph D. Kovic (A. G. Starr, O. K. Fuller, Jr., Fred Schultz)
Vance M. Lynch (J. B. Ferguson, R. J. St. Germain, E. E. Jones)
Edgar O. McCutchen (R. D. DeJournette, H. L. Grant, F. J. DiGiulio)
J. T. McMaster (R. I. Westmacott, H. F. Patterson, D. W. Ratliff)
Trevor W. Morrison (T. C. Richards, M. B. Dobrin, D. T. Germain-Jones)
Walter D. Paterson (Gordon B. Cloepfil, S. W. Fruehling, Joe Sides)
W. E. Shell (J. D. Marr, F. F. Reynolds, K. A. Webb, R. R. Rosenkrans)
Donald R. Smith (P. E. Dehlinger, J. A. Standridge, W. H. Mannes)
C. F. Wendenburg (Russell N. Ostreim, D. P. Melton, H. H. Happel, Jr.)
B. A. Woodham (Louis Poindexter, R. G. Mills, F. Ritchie Wallace)

RESOLUTIONS REGARDING JOINT MEETINGS OF AAPG AND SEG

March 7, 1956

RESOLUTION

WHEREAS the Society of Exploration Geophysicists and the American Association of Petroleum Geologists no longer meet jointly in annual sessions, due to difficulties incurred by the size of such meetings, and

WHEREAS an increasing need exists for mutual cooperation and coordination of scientific effort among geologists and geophysicists:

Be it hereby resolved by the executive committee of the Society of Exploration Geophysicists that it be the stated policy of the Society to encourage and urge all local geophysical sections and regional groups of sections to meet jointly with corresponding regional geological sections or groups, so that the spirit of cooperation and coordination existing in the past among geologists and geophysicists may be fostered and increased; and be it further resolved that all geophysical sections and regional groups be encouraged to take the initiative in framing invitations and programs to hold such meetings as joint partnership ventures; and further

be it resolved that copies of this resolution be mailed to all geological and geophysical societies and groups, and that this resolution be published in the several bulletins and journals of the many geological and geophysical societies.

By the Executive Committee of the
Society of Exploration Geophysicists

R. C. DUNLAP JR., *President*
DAVE CARLTON, *Vice-President*
G. A. GRIMM, *Secretary-Treasurer*
NORMAN RICKER, *Editor*
PAUL L. LYONS, *Past-President*

Fort Worth, Texas
March 7, 1956

RESOLUTIONS REGARDING JOINT MEETINGS OF AAPG AND SEG

RESOLUTION

WHEREAS, The American Association of Petroleum Geologists and the Society of Exploration Geophysicists no longer meet jointly in annual sessions, due to difficulties incurred by the size of such meetings, and

WHEREAS, an increasing need exists for mutual cooperation and coordination of scientific effort among geologists and geophysicists; now

THEREFORE, be it resolved by the Executive Committee of The American Association of Petroleum Geologists that regional sections and affiliated societies be encouraged to continue the spirit of cooperation and coordination existing in the past among geophysicists and geologists; and be it further resolved that such groups be encouraged to take the initiative in holding meetings jointly with geophysical groups; and

be it further resolved that copies of this resolution be mailed to all geological and geophysical societies and groups, and that the Executive Committee suggests that this resolution be published in the several bulletins and journals of the many geological and geophysical societies

By the Executive Committee of the
American Association of Petroleum Geologists

THEO. A. LINK, *President*
G. M. KNEBEL, *Past-President*
BEN H. PARKER, *V. President*
W. A. WALDSCHMIDT, *Secretary-Treasurer*
W. C. KRUMBEIN, *Editor*

Chicago, Illinois
April 21, 1956

ANNOUNCEMENTS

SOUTHWESTERN I.R.E. CONFERENCE

The Shamrock-Hilton Hotel in Houston will be the scene of the 1957 Southwestern I.R.E. Conference and Electronics Show. An attendance by 2,500 engineers and scientists is expected for the 3-day meeting. Featured at the conference will be three simultaneous sessions, one of which will be held by the National Simulation Council under the sponsorship of the I.R.E. Professional Group on Electronic Computers, otherwise known as the giant brains. Other highlights will be a meeting of the National I.R.E. Board of Directors, a featured speaker on the Earth Satellite program and the International Geophysical Year, and an elaborate ladies' program. In addition, there will be over 100 booths for the latest exhibits. The dates are April 11, 12, and 13, 1957.

INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS
ELEVENTH GENERAL ASSEMBLY
TORONTO 1957

The National Research Council, on behalf of the Government of Canada, has issued a circular inviting geophysicsts all over the world to attend the Eleventh General Assembly of the International Union of Geodesy and Geophysics which is to be held at the University of Toronto from September 3–14, 1957.

The Union meets regularly every three years, but the 1957 meetings, coming as they do during the International Geophysical Year, promise to arouse unusual interest among scientists, industry and the public. Forty-five countries are members of the Union. Seven Associations compose the Union: Geodesy, Geomagnetism and Aeronomy, Hydrology, Meteorology, Oceanography, Seismology and Physics of the Earth's Interior, and Volcanology. Some 1,000 to 1,500 scientists are expected to visit Toronto for the meetings, to report on their research and plan future cooperative efforts.

A feature of these international meetings will be an exhibition of the newest instruments, equipment and methods available for geophysical work.

DR. J. A. JACOBS, Secy.
Arrangements Committee
49 St. George Street
Toronto 5, Canada

PERSONAL ITEMS

Members of the Society are invited to notify the business manager of any changes in their positions or companies for announcement in this section. Members are further invited to check with the public relations departments of their companies to assure that the Society is on their mailing lists to receive publicity releases.

HERBERT HOOVER, JR. will receive the Hoover Medal, sponsored by the American Society of Civil Engineers, the American Institute of Mining, Metallurgical, and Petroleum Engineers, the American Society of Civil Engineers and the American Institute of Electrical Engineers jointly, in honor of his distinguished father.

FRANCIS M. LEHNER, formerly seismologist with Shell Oil Company, is now with Seismograph Service Corp. as West Coast representative. His office is at 221 E. Brundage Lane, Bakersfield, California.

A MEMBER OF THE SOCIETY would like to obtain the following out-of-print issues of GEOPHYSICS, v. 1, n. 1; v. 3, n. 4; v. 5, n. 1 and part 2 of n. 3; v. 6, nos. 2, 3 & 4; v. 7, nos. 1, 2 & 3; v. 8, nos. 1, 2: 3 & 4; v. 9, nos. 1, 2, 3, & 4; and v. 12, n. 3. These issues are needed to complete a set of the Journal for presentation to a university. Anyone who would sell his copies of these issues is asked to notify the Business Manager.

R. D. ROBERTS, Midcontinent Division Geophysicist for Sohio Petroleum Company, has been promoted to Manager of the company's Calgary office.

JAMES C. MENEFEE, Chief Geophysicist for Mobil Producing Company, Billings, Montana, has been temporarily assigned to the Paris Office of Mobil Oil Francaise.

NEAL CLAYTON is no longer associated as a partner with Miles Exploration Company. He is President of Liberty Exploration Company, Tulsa, Oklahoma.

JOHN S. SUMNER has taken the position of Manager with McPhar Geophysics, Inc., with offices at 5145 Upton Ave. S., Minneapolis, Minnesota.

RAY C. LEWIS has joined the Highland Oil Company and the Herman Brown and George R. Brown Oil & Gas Division as Executive Vice President and General Manager of Highland, and Assistant General Manager of the Oil and Gas Division.

WENDELL L. LEWIS has joined Highland Oil Company and Herman Brown & George R. Brown Oil & Gas Division as Vice President and Manager of Exploration of Highland, and Manager of Exploration of the Oil & Gas Division.

JAMES M. WILSON has been employed by Highland Oil Company and Herman Brown & George R. Brown Oil & Gas Division as Chief Geophysicist.

J. R. BRADLEY, JR., resigned as a partner in Texas Seismograph Company June 1, 1956 to organize his own firm, Bradley Exploration Company. He intends to specialize in short term work in the North Texas district.

WOJECH DOMZALSKI joined Hunting Geophysics Ltd. on May 1, 1956, as Chief Geophysicist.

ENDERS A. ROBINSON has joined the staff of the coordination and petroleum economics department of the Standard Oil Company (New Jersey).

ELISABETH STILES, former Business Manager of SEG (1945–1946), and a Charter Member of the Society, suffered a brain hemorrhage a year ago. At last report she was completely inactive, being

unable to write or communicate her thoughts except by signs. Her address is Circle S Ranch, Hamilton, Texas.

MAURICE EWING, professor of geology and director of Lamont Geological Observatory, Columbia University, has been elected to foreign membership by the Royal Netherlands Academy (Section for Sciences).

H. W. "HAYWIRE" BROWN resigned his position as Director of The Carter Oil Company to become representative for Europe and Africa on the New York staff of the Coordinator of Producing Activities, Standard Oil Company (New Jersey). He will make his home in Rome until early in 1957, at which time he will return to New York City.

JAMES WESLEY RICHARDSON died February 20, 1956 at St. John's Hospital in Tulsa after a short illness. Burial was at Coushatta, Louisiana. He is survived by his wife, Yetta M. Richardson, and his mother, Florence Butler. He joined Amerada Petroleum Corporation in July, 1926, where he worked as a permit man, party chief, and drilling supervisor. In December, 1952, he left Amerada to organize his own drilling company which he operated until his death.

JOHN J. COLLIER, JR. assumed the position of Assistant to the Division Manager in Exploration for The Pure Oil Company on May 1, 1956, in addition to his duties as Division Exploration Manager, Southwestern Producing Division.

WILLIAM H. JOHNSON is now Supervisor with National Geophysical Company of Canada, Ltd., Calgary.

DAYTON H. CLEWELL has accepted a position as manager of Socony Mobil Laboratories with headquarters in New York. Dr. Clewell has been manager of The Magnolia Petroleum Company's Field Research Laboratories in Dallas. He will be succeeded by C. I. Alexander, who has been supervisor of the exploration research division at the laboratories.

Election of HENRY C. CORTES to a Magnolia Petroleum Company vice-presidency has been announced. In his new post, Mr. Cortes will be in charge of coordination of the company's offshore operations, as well as holding his present duties as company director responsible for Magnolia's Field Research Laboratories. He was formerly assistant manager of the Exploration Division.

JOHN W. CLARK, former chief geologist for Magnolia Petroleum Company, has been named assistant manager of the Exploration Division. Mr. Clark succeeds Henry C. Cortes, who was recently elevated to a Magnolia vice-presidency. His appointment was effective September 1, 1956.

SOCIETY OF EXPLORATION GEOPHYSICISTS

Code of Ethics

The Constitution of the Society, Article IV, Section 1 states that, "Membership of any class shall be contingent upon conformance with the established principles of professional ethics."

As an elaboration of these established principles of professional ethics the following Code of Ethics is enunciated. It shall be the duty of every geophysicist, in order to maintain the dignity of his chosen profession:

1. To carry on his professional work in a spirit of fidelity to clients and employers, fairness to employees and contractors, and devotion to high ideals of personal honor.

2. To treat as confidential his knowledge of the business affairs, geophysical or geological information, or technical processes of clients or employers when their interests require secrecy.

3. To inform a client or employer of any business connections, or affiliations which might influence his judgment or impair the disinterested quality of his services.

4. To accept financial or other compensation for a particular service from one source only, except with the full knowledge and consent of all interested parties.

5. To refrain from associating himself with, or knowingly to allow the use of his name by, any enterprise of questionable character.

6. To advertise only in a manner consistent with the dignity of the profession, to refrain from using any improper or questionable methods of soliciting professional work, and to decline to pay or to accept compensation for work secured by such improper or questionable methods.

7. To refrain from using unfair means to win professional advancement, and to avoid injuring unfairly or maliciously, directly or indirectly another geophysicist's professional reputation, business, or chances of employment.

8. To cooperate in building up the geophysical profession by the interchange of general information and experience with his fellow geophysicists and with students and also by contributions to the work of technical societies, schools of applied science, and the technical press.

9. To interest himself in the public welfare and to be ready to apply his special knowledge, skill, and training in the public behalf for the use and benefit of mankind.

PROPOSED AMENDMENTS TO SOCIETY OF EXPLORATION GEOPHYSICISTS CONSTITUTION AND BYLAWS

(Words to be deleted are shown in parentheses and words to be added are *italicized*.)

CONSTITUTION

Article III. Membership

Section 2. The membership of this Society shall consist of Honorary Members, Active Members, Associate Members, (and) Student Members, *and Sustaining Members*.

Section 3. To be eligible to election to Honorary Membership a person shall, in the unanimous opinion of the (Standing) Committee on Honors and Awards and the (Council) *Executive Committee*, have made a distinguished contribution to geophysics or a related field which warrants exceptional recognition.

Section 6. To be eligible to election to Student Membership an applicant must be a graduate or undergraduate student in good standing in residence at a recognized university or college. *Eligibility for Student Membership shall terminate at the close of the calendar year in which the Student Member ceases to be a graduate or undergraduate student in good standing in residence at a recognized university or college.*

Section 7. To be eligible to election to Sustaining Membership, an individual or company must have an active interest in supporting the objects of this Society.

Renumber Sections 7 and 8 as Sections 8 and 9 respectively.

Article VI. Officers

Section 2. Election of officers shall be by secret mail ballot. On the ballot shall be printed the nominees for each office arranged in (alphabetical order) *a fair manner*.

Section 3. *There shall be a Committee on Nominations consisting of the President who shall be Chairman, the Past President, and the Prior Past President.* The committee on Nominations shall nominate, in the manner prescribed in the Bylaws, two candidates for each office to be filled. Further nominations may be made by petition as set forth in the Bylaws.

Section 4. The officers shall assume the duties of their respective offices (immediately after the close of) *at the Joint Council Meeting during* the Annual Meeting following their election. *Each officer shall assume his duties upon completion of the presentation of the report of his predecessor.*

Section 6. In case of a vacancy in any office, other than the President's, the Executive Committee shall select a successor to serve until (the close of) the Annual Meeting following this appointment.

Article VII. Duties of Officers

Section 1. The President shall be the presiding officer at all the meetings of the Society, shall take cognizance of the acts of the Society and of its officers, shall appoint such (standing) committees (and special committees) as are required for the purposes of the Society, and shall delegate members to represent the Society. He may, at his option, serve on, and may be chairman of, any committee He shall prepare an address to be given before the members of the Society at the Annual Meeting.

Section 2. The Vice-President shall assume the office of President in case of a vacancy from any cause in that office and shall assume the duties of President (in case of) *during* the absence or disability of the latter. He shall also be responsible for all national meetings of the Society. *He shall perform such other duties as may be delegated to him by the President.*

Section 3. The Secretary-Treasurer shall assume the duties of the President (in case of) *during* the absence of both the President and Vice-President. He shall have charge of the financial affairs of the Society and shall annually submit reports as Secretary-Treasurer covering the fiscal year, which he shall arrange to have published in the next regular issue of the journal of the Society. Under the direction of the Council, he shall arrange for the receipt and disbursal of all Society funds. He shall cause an audit to be prepared annually by a public accountant at the expense of the Society. He shall give a bond, and shall cause to be bonded, all employees to whom authority may be delegated to handle Society funds. The amount of such bonds shall be set by the Council and the expense shall be borne by the Society.

Article VIII. Council

Section 1. The Council of the Society shall consist of the officers, the Past President, the Prior Past President, (and all elected) District Representatives, *and Representatives-at-large.*

Section 3. A joint meeting of the outgoing and incoming Councils shall be held at the call and under the chairmanship of the (newly elected) *outgoing* President during (or within seven days after) the Annual Meeting of the Society. At this joint meeting the Councils shall hear reports from all officers and committees and review the activities of the Society for the past year. With the advice of the outgoing Council, the incoming Council *under the chairmanship of the incoming President* shall conduct any necessary business and issue instructions or recommendations to any officer or committee, subject to the provisions of the Constitution and Bylaws. All committee chairmen shall attend this meeting, but, as chairmen, shall have no vote.

Section 5. A quorum at any meeting of the Council shall consist of (six) *one-third of all* Council members.

Article X. Meetings

Section 1. The society shall hold at least one meeting of the members each year, this meeting to be known as the Annual Meeting. One session of this meeting shall be a Business Meeting, at which reports of the officers and committees shall be (read and the result of the mail ballot for officers announced) *presented and the newly elected officers introduced.*

Article XI. Local Sections

Section 2. Each local section shall assist in carrying out the objectives of the Society (within the territory assigned to the section by the Council).

Section 3. Each local section shall have one District Representative if among its members there are (less) *not more* than seventy-five Honorary Members and Active Members of the Society in good standing, two District Representatives if more than seventy-five and (less) *not more* than one hundred fifty, or three District Representatives if more than one hundred fifty.

Delete entire Article XII and add new Article XII.

Article XII. *Representatives-at-Large*

Section 1. The number of Representatives-at-large shall be specified in the Bylaws but shall not be less than three.

Section 2. Representatives-at-large shall be elected from among the Honorary Members and Active Members of the Society in good standing for terms stated and in the manner prescribed in the Bylaws and shall not be eligible for two consecutive terms.

Section 3. Representatives-at-large shall have all the rights and authority of District Representatives.

Delete entire present Article XIV and add the following new sections.

ARTICLE XIV. COMMITTEES

Section 1. The President may at any time appoint committees for such purposes as he may deem fit to further the purposes of the Society.

Section 2. The terms of all committees shall expire at the close of the Annual Meeting following their appointment unless otherwise specified in the Constitution or Bylaws.

Section 3. The Chairman of each Committee shall make an Annual Report at the Council Meeting during the Annual Meeting. He shall make interim reports at the request of the President.

ARTICLE XVII. BYLAWS *AND PROCEDURES MANUAL*

Section 2. A Procedures Manual, not in conflict with the Constitution and Bylaws, shall govern the details of the operation of the Society. This Manual shall be prepared by the Business Manager and shall be revised by him from time to time. This Manual and any changes to it must be approved by the Executive Committee.

BYLAWS

ARTICLE I. PUBLICATIONS

Section 3. All reports to the Society by its officers and committees shall be published in the journal. All members of the Society shall be presumed to have due notice of all Society matters published in the journal. Each issue shall contain a membership list of all (standing and special) Committees.

Section 5. The subscription rate of the journal shall be ($9.00 ($9.50 foreign) per year to non-members and $4.50 per year to members) *set by the Council.* (The first $4.50) *At least half* of the annual dues of each dues paying member shall be set aside for the payment of his subscription to the journal. Members of affiliated societies shall be entitled to receive the journal upon payment of a fee equivalent to the dues charged to an associate member.

ARTICLE II. ELECTION OF HONORARY MEMBERS

Section 1. The (Standing) Committee on Honors and Awards may submit to the President ninety days before the Annual Meeting the names of any person or persons they deem eligible to election as an Honorary Member. Their report shall explain the basis of their recommendation.

Section 2. The President shall submit copies of any such reports to all members of the (Council) *Executive Committee* not less than sixty days before the Annual Meeting.

Section 3. The (Council) *Executive Committee* members shall consider all such reports and vote by mail thirty days before the Annual Meeting. Unanimous action by those voting shall be required to elect any person as an Honorary Member.

Section 4. The Committee on Honors and Awards shall consist of five Active or Honorary Members, none of whom shall have been members of the Society less than five years. The senior member of the committee shall retire after the Annual Meeting. Vacancies shall be filled by the President. The Committee shall recommend candidates for all established honors and awards of the Society and for election to Honorary Membership to the Executive Committee.

Section 5. The Committee on Honors and Awards shall recommend to the Council the establishment of honors and awards.

ARTICLE III. ELECTION TO ACTIVE, ASSOCIATE (AND) STUDENT, *AND SUSTAINING* MEMBERSHIP

Section 5. An applicant for Active (or) Associate, *or Sustaining* membership must be approved by a majority of the Executive Committee. An applicant for Student membership must be approved by the Secretary-Treasurer.

Section 7. An Associate or Student Member may seek transfer to Active Membership by supplying added information to show that he has become eligible to election to Active Membership. The (Standing) Committee on Membership may of its own initiative secure the necessary added information and submit it to the Executive Committee. The transfer shall be handled in the same manner as election to Active Membership. *A Student Member shall automatically be transferred to Associate Membership on the first day of the calendar year following the termination of his eligibility to Student Membership.*

ARTICLE IV. DUES

Section 2. The annual dues of an Active (or Associate) Member of the Society shall be (seven dollars and fifty cents $7.50) *ten dollars ($10.00)* which includes the cost of one subscription to the Society's journal. *The annual dues of an Associate Member of the Society shall be eight dollars and fifty cents ($8.50) for a period of five years and ten dollars ($10.00) thereafter, which includes the cost of one subscription to the Society's journal.*

Section 4. The annual dues of a Sustaining Member of the Society shall be one hundred dollars ($100.00) or such larger amount as the Sustaining Member may designate.

Section 5. (Present Section 4, renumbered and modified) Annual dues shall be payable in advance on January 1 of the calendar year. A bill shall be mailed to each Active, Associate, or Student Member before that date, stating the amount of annual dues and the penalty for default. The Society's journal shall be withheld from members pending payment of dues, and Active Members failing to pay by (ten days prior to the Annual Meeting) *June 1* shall have their votes in the annual mail ballot disqualified. Members in arrears shall lose all privileges of membership until such arrears are met.

ARTICLE VII. ELECTION OF OFFICERS

Delete present Section 1.

Section 1. (Present Section 2, renumbered and modified) The (Standing) Committee on Nominations shall nominate two or more candidates for each office to be filled *including Representatives-at-large.* They must secure the consent of all candidates nominated.

Section 2. (Present Section 3, renumbered and modified) The (Standing) Committee on Nominations must submit their ticket to the President in time for publication in the April issue of the Society's journal.

Section 3. (Present Section 4, renumbered) Prior to June 1, nominations in writing, signed by at least twenty Honorary Members or Active Members in good standing and accompanied by the written consent of the candidate, may be submitted to the President.

Section 4. (Present Section 5, renumbered and modified) Between June 1 and June 15, the Business Manager will prepare and mail to each member eligible to vote, a ballot listing all candidates properly nominated for each office *including District Representatives and Representatives-at-large.* With each ballot, the business manager shall send an official envelope having the member's name on the back.

Section 5. (Present Section 6, renumbered and modified) The (Standing) Committee on Nominations shall appoint a committee of tellers to count the ballots.

Section 6. (Present Section 7, renumbered and modified) Each member voting may cast one vote for each officer *and for either the indicated number of Representatives-at-large or of District Representatives from a single local Section* and shall return his ballot to the business manager in the official envelope carrying on the outside the written signature of the member submitting the ballot. Only ballots so prepared by members in good standing, and received by the business manager at his officially recognized address not later than July 31, shall be valid.

Section 7. (Present Section 8, renumbered and modified) The business manager shall indicate which ballots are valid, and shall deliver all ballots unopened to the tellers after August 1. The candidate receiving the greatest number of valid votes cast for an office shall be declared elected to that office. In case of a tie, the (Standing) Committee on Nominations shall decide by a secret vote which of the candidates shall be elected. Results of the mail ballot shall be communicated to all candidates by the nominating committee on or before August 15.

ARTICLE VIII. LOCAL SECTIONS

Section 1. Upon petition of twenty members *of any grade* in good standing residing within an appropriate distance of a central point, the Council may authorize the formation of a Local Section (and assign a specific territory to the Local Section). The Council may decline to authorize the formation of a Local Section when in its judgment such an organization would not be compatible with the interests of the Society.

Delete present Section 2, 3, and 4.

Section 2. (Present Section 5, renumbered) The section shall adopt bylaws which must be approved by the Council of the Society and shall be consistent with the Constitution and Bylaws of the Society.

Section 3. (Present Section 6, renumbered and modified) (The election of District Representatives by the Local Sections shall be by secret ballot.) The term of office of a District Representative shall be two years; however, if the section is entitled to more than one representative, one of the representatives elected at the establishment of the section or added as the result of subsequent growth of the Section, shall be elected for a one year term if this is necessary to prevent the terms of all District Representatives from expiring simultaneously. *The Local Section shall nominate in the manner prescribed by its Bylaws of nominating section officers, two candidates for each District Representative to be elected and submit their names to the President of the Society prior to June 1.*

Delete Sections 7 and 8.

Section 4. (Present Section 9, renumbered and modified) (Any Local Section which for two consecutive years has among its membership fewer than twenty members in good standing of the Society shall automatically be dissolved by the Council at its annual joint meeting.) The Council may at any time dissolve any Local Section for reasons it deems good and sufficient.

Delete entire present Article IX and add new Article IX.

ARTICLE IX. *REPRESENTATIVES-AT-LARGE*

Section 1. The number of Representatives-at-large shall be three. The term of a Representative-at-large shall be two years, except that one of the Representatives-at-large elected in 1957 shall serve a single year.

Delete entire Article X.

SOCIETY OF EXPLORATION GEOPHYSICISTS
CONSTITUTION AND BYLAWS

CONSTITUTION

(As amended to August 26, 1948)

Article I.	Name	Article X.	Meetings
Article II.	Object	Article XI.	Local Sections
Article III.	Membership	Article XII.	Districts
Article IV.	Code of Ethics	Article XIII.	Affiliated Societies
Article V.	Election, etc. of Members	Article XIV.	Committees
Article VI.	Officers	Article XV.	Business Manager
Article VII.	Duties of Officers	Article XVI.	Review by Members
Article VIII.	Council	Article XVII.	Bylaws
Article IX.	Executive Committee	Article XVIII.	Amendments to the Constitution

Article I. Name

Section 1. The Society shall be called the "Society of Exploration Geophysicists."

Article II. Object

Section 1. The objects of this Society shall be to promote the science of geophysics especially as it relates to exploration and research, to foster the common scientific interests of geophysicists, and to maintain a high professional standing among its members.

Article III. Membership

Section 1. The membership of this Society shall consist of persons elected and qualified in accordance with the Constitution and Bylaws of this Society at the time of such election.

Section 2. The membership of this Society shall consist of Honorary Members, Active Members, Associate Members, and Student Members.

Section 3. To be eligible to election to Honorary Membership a person shall, in the unanimous opinion of the Standing Committee on Honors and Awards and the Council, have made a distinguished contribution to geophysics or a related field which warrants exceptional recognition.

Section 4. To be eligible to election to Active Membership an applicant must have been actively engaged in practicing or teaching geophysics or a related field for not less than eight years (up to four years as a student in a recognized college or university may be counted toward this total) of which at least three years must have involved work of a responsible nature calling for independent judgment and the application of geophysical or geological principles.

Section 5. To be eligible to election to Associate Membership, an applicant must be actively interested in geophysics.

Section 6. To be eligible to election to Student Membership an applicant must be a graduate or undergraduate student in good standing in residence at a recognized university or college.

Section 7. An Honorary Member or Active Member shall enjoy all privileges of the Society. He shall be eligible to hold any office, to vote on all matters submitted to the membership, to petition the Council or Executive Committee on any matter, to sponsor applicants for membership and to publish his affiliation with the Society.

Section 8. An Associate Member or Student Member shall be entitled to attend the meetings of the Society, to receive its journal and to purchase its publications, on the same terms as an Active Member. He shall have none of the other privileges of membership and in publishing his affiliation with the Society shall clearly indicate his grade of membership.

Article IV. Code of Ethics

Section 1. Membership of any class shall be contingent upon conformance with the established principles of professional ethics.

Article V. Election, Resignation and Expulsion of Members

Section 1. The method of election to the various grades of membership shall be as set forth in the Bylaws.

Section 2. Any member in good standing may resign from the Society at any time as set forth in the Bylaws.

Section 3. Any member may for the good of the Society be suspended or expelled from the Society at any time as set forth in the Bylaws.

Article VI. Officers

Section 1. The officers of the Society shall be a President, a Vice-President, a Secretary-Treasurer, and an Editor. Officers shall be elected in the manner prescribed in the Bylaws for a term of one year with the exception of the Editor, whose term shall be two years.

Section 2. Election of officers shall be by secret mail ballot. On the ballot shall be printed the nominees for each office arranged in alphabetical order.

Section 3. The Standing Committee on Nominations shall nominate, in the manner prescribed in the Bylaws, two candidates for each office to be filled. Further nominations may be made by petition as set forth in the Bylaws.

Section 4. The officers shall assume the duties of their respective offices immediately after the close of the Annual Meeting following their election.

Section 5. No officer shall be eligible for election to the same office for two consecutive terms.

Section 6. In case of a vacancy in any office, other than the President's, the Executive Committee shall select a successor to serve until the close of the Annual Meeting following this appointment.

Article VII. Duties of Officers

Section 1. The President shall be the presiding officer at all the meetings of the Society, shall take cognizance of the acts of the Society and of its officers, shall appoint such standing committees and special committees as are required for the purposes of the Society, and shall delegate members to represent the Society. He may, at his option, serve on, and may be chairman of, any committee. He shall prepare an address to be given before the members of the Society at the Annual Meeting.

Section 2. The Vice-President shall assume the office of President in case of a vacancy from any cause in that office and shall assume the duties of President in case of the absence or disability of the latter. He shall also be responsible for all national meetings of the Society.

Section 3. The Secretary-Treasuer shall assume the duties of the President in case of the absence of both the President and Vice-President. He shall have charge of the financial affairs of the Society and shall annually submit reports as Secretary-Treasurer covering the fiscal year, which he shall arrange to have published in the next regular issue of the journal of the Society. Under the direction of the Council, he shall arrange for the receipt and disbursal of all Society funds. He shall cause an audit to be prepared annually by a public accountant at the expense of the Society. He shall give a bond, and shall cause to be bonded, all employees to whom authority may be delegated to handle Society funds. The amount of such bonds shall be set by the Council and the expense shall be borne by the Society.

Section 4. The Editor shall be in charge of the editorial business, shall submit an annual report of such business, shall have authority to solicit papers and material for the regular Society publication and for special publications, and may accept or reject material offered for publication. He may appoint associate, regional, and special editors.

Article VIII. Council

Section 1. The Council of the Society shall consist of the officers, the Past President, the Prior Past President, and all elected District Representatives.

Section 2. The Council shall be the governing body of the Society and subject to the provisions of the Constitution and Bylaws shall have full control and management of the affairs and funds of the society.

SECTION 3. A joint meeting of the outgoing and incoming Councils shall be held at the call and under the chairmanship of the newly elected President during or within seven days after the Annual Meeting of the Society. At this joint meeting the Councils shall hear reports from all officers and committees and review the activities of the Society for the past year. With the advice of the outgoing Council, the incoming Council shall conduct any necessary business and issue instructions or recommendations to any officer or committee, subject to the provisions of the Constitution and Bylaws. All committee chairmen shall attend this meeting, but, as chairmen, shall have no vote.

SECTION 4. At the call of the President or a majority of the Council members, and after written notice to all Council members, the Council may meet at any time.

SECTION 5. A quorum at any meeting of the Council shall consist of six Council members.

SECTION 6. Unless otherwise provided by the Constitution, all actions by the Council shall require a majority vote of the members present.

ARTICLE IX. EXECUTIVE COMMITTEE

SECTION 1. The Executive Committee shall consist of the President, the Vice-President, the Secretary-Treasurer, the Editor, and the Past President.

SECTION 2. When the Council is not in session the Executive Committee shall have full authority, subject only to prior instructions by the Council, to exercise all powers of the Council.

SECTION 3. All actions of the Executive Committee shall require a majority vote of all members of the Committee.

SECTION 4. The Executive Committee may vote an any matter either by mail or in person.

ARTICLE X. MEETINGS

SECTION 1. The Society shall hold at least one meeting of the members each year, this meeting to be known as the Annual Meeting. One session of this meeting shall be a Business Meeting, at which reports of the officers and committees shall be read and the result of the mail ballot for officers announced.

SECTION 2. The Annual Meeting shall be held at a time and place designated by the Executive Committee.

SECTION 3. Additional meetings of the Society may be called by the Executive Committee.

ARTICLE XI. LOCAL SECTIONS

SECTION 1. Local sections, consisting of members of the Society and other persons engaged in geophysics or a related field residing within an appropriate distance of a central point, may be organized as provided in the Bylaws.

SECTION 2. Each local section shall assist in carrying out the objectives of the Society within the territory assigned to the section by the Council.

SECTION 3. Each local section shall have one District Representative if among its members there are less than seventy-five Honorary Members and Active Members of the Society in good standing, two District Representatives if more than seventy-five and less than one hundred fifty, or three District Representatives if more than one hundred fifty.

SECTION 4. The District representatives shall be elected from among the Honorary Members and Active Members of the Society in good standing for terms stated and in the manner prescribed in the By laws and shall not be eligible for two consecutive terms.

ARTICLE XII. DISTRICTS

SECTION 1. The Council shall divide the area of the continental United States, not assigned to local sections, into not more than seven districts. Council may designate districts outside the area of the continental United States.

SECTION 2. Each district shall have for each seventy-five Active Members of the Society, who are not members of a local section, one District Representative, who shall be appointed by the President for a term of one year expiring at the close of the Annual Meeting.

Article XIII. Affiliated Societies

Section 1. The Council may arrange for affiliation of the Society with any duly organized groups or societies.

Section 2. The terms of affiliation must provide that the Society shall have the right to dissolve such affiliation at any time, subject only to the payment of any sums it may legally owe the affiliated group or society.

Article XIV. Committees

Section 1. In addition to the Executive Committee, there shall be appointed standing committees to further the purposes of the Society.

Section 2. The duties of the standing committees and the method of their appointment shall be in accordance with the Bylaws.

Section 3. The President may at any time appoint special committees for such purposes as he may deem fit.

Section 4. The terms of all special committees shall expire at the close of the Annual Meeting following their appointment.

Article XV. Business Manager

Section 1. The Council may employ a business manager for the Society and pay him such salary and other compensations from the Society's funds as they deem advisable.

Section 2. The business manager shall provide a bond appropriate in amount, the cost to be borne by the society.

Section 3. The business manager shall, under the supervision of the Secretary-Treasurer, perform such duties as the Council may assign him.

Section 4. The Council may discharge the business manager at any time.

Article XVI. Review by Members

Section 1. All acts of the officers, Council, and committees of the Society shall be subject to review by the members.

Section 2. Proposals to change any decision, policy, or procedure of any officer, the Council, or any committee shall be submitted in writing to the President and signed by at least twenty-five Honorary and Active Members in good standing.

Section 3. Upon receipt of such a petition with a sufficient number of valid signatures, the President shall advise the Council and the officer or committee involved.

Section 4. Should the officer or committee involved be unwilling to comply with the petition, it, together with a discussion by the proposer and the officer or committee involved, shall be published in the next issue of the Society's journal.

Section 5. Within thirty days after publication in the journal, the petition shall be submitted to the membership by mail ballot by the President. A majority of the ballots returned within thirty days after being mailed by the President shall be decisive. Should the vote favor the petition, it shall be complied with, within the limitations imposed by the Constitution and Bylaws, as promptly as practicable.

Article XVII. Bylaws

Section 1. The Council shall make such Bylaws not in conflict with the Constitution, as it may deem necessary for the proper government of the Society. The Council may amend the Bylaws at the annual joint meeting by an affirmative vote of two-thirds of the members of the incoming Council present. All proposed amendments must, however, be published in the Society's journal before being submitted to the Council.

Article XVIII. Amendments to the Constitution

Section 1. Amendments to this Constitution may be proposed by any ten members of the Society, by any officer of the Society, or by a Constitutional Committee appointed by the President.

Section 2. Any proposed amendment shall be submitted to the President in time for publication in the Society's journal prior to the Annual Meeting.

Section 3. At the annual joint meeting of the Council, all proposed amendments received since the previous Annual Meeting, shall be considered. Those receiving approval from a majority of the members of the incoming Council present shall be submitted by mail ballot, arranged by the Secretary-Treasurer, to the entire membership of the Society within sixty days. If a majority of the ballots returned within sixty days of their mailing favor the proposed amendment, it shall become effective at the expiration of this sixty days. All amendments shall be reported in the Society's journal.

BYLAWS

(As amended to July 16, 1954)

Article I. Publications
Article II. Election of Honorary Members
Article III. Election of Active, Associate and Student Members
Article IV. Dues
Article V. Resignation of Members
Article VI. Expulsion of Members
Article VII. Election of Officers
Article VIII. Local Sections
Article IX. Finances of Local Sections
Article X. Standing Committees

Article I. Publications

Section 1. The Society shall publish a journal entitled Geophysics.

Section 2. The journal shall be published at intervals designated by the Executive Committee.

Section 3. All reports to the Society by its officers and committees shall be published in the journal. All members of the Society shall be presumed to have due notice of all Society matters published in the journal. Each issue shall contain a membership list of all standing and special Committees.

Section 4. Original papers, reviews, abstracts, notes or letters containing information deemed by the Editor to be of interest to the members of the Society shall be published in the journal. The Editor shall be the sole judge of whether such material is to be published.

Section 5. The subscription rate of the journal shall be $9.00 ($9.50 foreign) per year to non-members and $4.50 per year to members. The first $4.50 of the annual dues of each dues paying member shall be set aside for the payment of his subscription to the journal. Members of affiliated societies shall be entitled to receive the journal upon payment of a fee equivalent to the dues charged to an associate member.

Section 6. The Council may at its annual joint meeting authorize the printing of special publications to be financed and distributed in a manner approved by the Council.

Article II. Election of Honorary Members

Section 1. The Standing Committee on Honors and Awards may submit to the President ninety days before the Annual Meeting the names of any person or persons they deem eligible to election as an Honorary Member. Their report shall explain the basis of their recommendation.

Section 2. The President shall submit copies of any such reports to all members of the Council not less than sixty days before the Annual Meeting.

Section 3. The Council members shall consider all such reports and vote by mail thirty days before the Annual Meeting. Unanimous action by those voting shall be required to elect any person as an Honorary Member.

Article III. Election to Active, Associate, and Student Membership

Section 1. An applicant for election to Active, Associate, or Student Membership shall submit to the business manager of the Society an application setting forth in detail his education and experience. The application shall list the names and present addresses of persons who can verify the statements given therein. It shall list not less than three Active Members or Honorary Members of the Society, in good standing, who are personally acquainted with the training or experience of the applicant. This application shall be open to inspection at any time.

Section 2. The Executive Committee may waive the requirement of references from members of the Society for geographical or other reasons, if the applicant is otherwise eligible and furnishes other satisfactory references.

Section 3. The business manager shall write to all references for verification of the applicant's statements. All replies from references shall be considered confidential and shall not be disclosed except to the Executive Committee, without the references' prior written consent.

Section 4. The name of each applicant for Active membership shall be published in the next regular issue of the Society's journal for approval by the membership at large. If no objection is received within thirty days after this publication, the applicant shall be deemed approved by the membership at large.

Section 5. An applicant for Active or Associate membership must be approved by a majority of the Executive Committee. An applicant for Student membership must be approved by the Secretary-Treasurer.

Section 6. When an applicant has been approved, he shall be notified in writing by the Business Manager. If he fails to make payment of full annual dues within four months after such notification, the Executive Committee may rescind his election. His membership shall date from the first day of the calendar year in which he makes his initial payment of dues and he shall receive the regular Society publications for that year.

Section 7. An Associate or Student Member may seek transfer to Active Membership by supplying added information to show that he has become eligible to election to Active Membership. The transfer shall be handled in the same manner as election to Active Membership. The Standing Committee on Membership may of its own initiative secure the necessary added information and submit it to the Executive Committee.

Article IV. Dues

Section 1. Honorary members shall not be required to pay dues and shall receive the journal and other publications without charge.

Section 2. The annual dues of an Active or Associate Member of the Society shall be seven dollars and fifty cents ($7.50), which includes the cost of one subscription to the Society's journal.

Section 3. The annual dues of a Student Member of the Society shall be four dollars and fifty cents ($4.50), which includes the cost of one subscription to the Society's journal.

Section 4. Annual dues shall be payable in advance on January 1 of the calendar year. A bill shall be mailed to each Active, Associate, or Student Member before that date, stating the amount of annual dues and the penalty for default. The Society's journal shall be withheld from members pending payment of dues, and Active Members failing to pay by ten days prior to the Annual Meeting shall have their votes in the annual mail ballot disqualified. Members in arrears shall lose all privileges of membership until such arrears are met.

Article V. Resignation of Members

Section 1. Any member of the Society may resign at any time. Such resignation shall be submitted in writing to the Council.

Section 2. Any member who resigns under the provisions of Section 1 of this Article ceases to have any rights in the Society and ceases to incur further indebtedness to the Society.

Section 3. Any person who has ceased to be a member under Section 1 of this Article may be re-

instated by unanimous vote of the Executive Committee subject to the payment of any outstanding dues and obligations which were incurred prior to the date when he ceased to be a member of the Society.

Article VI. Expulsion of Members

Section 1. Any member who fails to pay his dues by the last day of the calendar year shall be automatically suspended from membership on that day. While he is suspended, he shall have no rights in the Society and shall not be charged any dues.

Section 2. A member who has been suspended more than one year shall be dropped from the Society by the Executive Committee.

Section 3. A suspended member will automatically be reinstated by payment of outstanding dues and obligations and the dues for the current calendar year.

Section 4. A member who has been dropped under the provisions of Section 2 of this Article may be reinstated by a majority vote of the Executive Committee subject to the payment of outstanding dues and obligations and the dues for the current calendar year.

Section 5. Any member who, after being granted a hearing by the Executive Committee, shall be found guilty of a violation of the established principles of professional ethics, or shall be found guilty of having made a false or misleading statement in his application for membership in the Society, shall be asked to resign from the Society by unanimous vote of the Executive Committee. The decision of the Executive Committee in all matters pertaining to the interpretation and execution of the provisions of this section shall be final.

Article VII. Election of Officers

Section 1. The Standing Committee on Nominations shall consist of the President, the Past President, and the Prior Past President.

Section 2. The Standing Committee on Nominations shall nominate two or more candidates for each office to be filled. They must secure the consent of all candidates nominated.

Section 3. The Standing Committee on Nominations must submit their ticket to the President in time for publication in the April issue of the Society's journal.

Section 4. Prior to June 1, nominations in writing, signed by at least twenty Honorary Members or Active Members in good standing and accompanied by the written consent of the candidate, may be submitted to the President.

Section 5. Between June 1 and June 15, the Business Manager will prepare and mail to each member eligible to vote, a ballot listing all candidates properly nominated for each office. With each ballot, the business manager shall send an official envelope having the member's name on the back.

Section 6. The Standing Committee on Nominations shall appoint a committee of tellers to count the ballots.

Section 7. Each member voting may cast one vote for each officer and shall return his ballot to the business manager in the official envelope carrying on the outside the written signature of the member submitting the ballot. Only ballots so prepared by members in good standing, and received by the business manager at his officially recognized address not later than July 31, shall be valid.

Section 8. The business manager shall indicate which ballots are valid, and shall deliver all ballots unopened to the tellers after August 1. The candidate receiving the greatest number of valid votes cast for an office shall be declared elected to that office. In case of a tie, the Standing Committee on Nominations shall decide by a secret vote which of the candidates shall be elected. Results of the mail ballot shall be communicated to all candidates by the nominating committee on or before August 15.

Article VIII. Local Sections

Section 1. Upon petition of twenty members in good standing residing within an appropriate distance of a central point, the Council may authorize the formation of a Local Section and assign a specific territory to the Local Section. The Council may decline to authorize the formation of a Local

Section when in its judgment such an organization would not be compatible with the interests of the Society.

SECTION 2. In the organizing meeting of the section, all members of the Society residing in the territory assigned by the Council to the section shall be eligible to vote.

SECTION 3. The section shall be known as "The (name of place) Section of the Society of Exploration Geophysicists."

SECTION 4. The principal work of a section shall be the holding of regular meetings for the presentation and discussion of papers of interest to its members.

SECTION 5. The section shall adopt bylaws which must be approved by the Council of the Society and shall be consistent with the Constitution and Bylaws of the Society.

SECTION 6. The election of District Representatives by the Local Sections shall be by secret ballot. The term of office of a District Representative shall be two years; however, if the section is entitled to more than one representative, one of the representatives elected at the establishment of the section or added as the result of subsequent growth of the Section, shall be elected for a one year term if this is necessary to prevent the terms of all District Representatives from expiring simultaneously.

SECTION 7. District Representatives shall be elected at least three weeks prior to the Annual Meeting of the Society and shall take office at the close of the Annual Meeting.

SECTION 8. The Secretary of the Local Section shall submit to the Secretary-Treasurer of the Society a report of each meeting of the Local Section or its governing board within two weeks after the meeting. He shall submit to the Secretary-Treasurer of the Society the names of all officers and committee members within two weeks after their election or appointment.

SECTION 9. Any Local Section which for two consecutive years has among its membership fewer than twenty members in good standing of the Society shall automatically be dissolved by the Council at its annual joint meeting. The Council may at any time dissolve any Local Section for reasons it deems good and sufficient.

ARTICLE IX. FINANCES OF LOCAL SECTIONS

SECTION 1. The Society may, at the discretion of the Council, pay any portion of the necessary operating expenses of a Local Section up to the sum of the following amounts: (a) $100 per year; (b) $50 per meeting up to four meetings per year; (c) $0.50 per member of the Society.

SECTION 2. The Treasurer of the Local Section shall forward, from time to time, his application for such portions of the sum provided in Section 1 as may be needed to the Secretary-Treasurer of the Society, who will arrange for the issuance of a check for the requested amount to the Treasurer of the Local Section.

SECTION 3. Prior to the Annual Meeting, the Treasurer of each Local Section shall transmit to the Secretary-Treasurer of the Society, for approval by the Council, an itemized statement of the expenditure of the funds received from the Society during the preceding calendar year.

SECTION 4. Allocations to a Local Section for the year in which it is established shall be in proportion to the fraction of the calendar year remaining.

SECTION 5. The Local Section may levy dues or raise funds in any other manner, subject to the approval of the Council. Payment of local dues shall, however, not be a prerequisite to participation in any activity financed wholly or in part with funds received from the Society.

ARTICLE X. STANDING COMMITTEES

SECTION 1. The Society shall have the following standing committees: (a) Standing Committee on Nominations; (b) Standing Committee on Membership; (c) Standing Committee on Honors and Awards; (d) Standing Committee on Publications; (e) one or more General Committees for the Annual Meetings; (f) Standing Committee on Education; (g) Standing Committee on Student Membership; (h) Standing Committee on Distinguished Lectures; (i) Standing Committee on Radio Facilities; (j) Standing Committee on Reviews; (k) Standing Committee on Public Relations; (l)

Standing Committee on Publicity; (m) Standing Committee on Geophysical Activity; and (n) Standing Committee on Safety.

SECTION 2. Each standing committee shall have a chairman, appointed by the President unless otherwise specified in these Bylaws. The chairman shall submit a report to the President of the Society at such intervals as the chairman may deem advisable but at least quarterly. He shall submit to the Council at its annual joint meeting a report covering the activities of the committee since the previous Annual Meeting.

SECTION 3. The Standing Committee on Nominations shall consist of the President who shall be chairman, the Past President, and Prior Past President. Its duties shall be to nominate candidates for officers, appoint tellers to count the ballots, and to declare the election of the officers as prescribed in Article VII of these Bylaws.

SECTION 4. The Standing Committee on Membership shall consist of three Active or Honorary Members appointed for a period of one year by the President immediately following the Annual Meeting. One of the members appointed shall have been a member the preceding year. The Committee shall actively solicit applications for membership from those qualified. It shall work closely within the membership committees of the Local Sections.

SECTION 5. The Standing Committee on Honors and Awards shall consist of five Active or Honorary Members, none of whom shall have been members of the Society less than five years. The senior member of the committee shall retire after the Annual Meeting. Vacancies shall be filled by the President. The Committee shall recommend candidates for election to Honorary Membership to the Council. The Committee shall recommend to the Council the establishment of honors and awards and shall recommend candidates for all established honors and awards of the Society to the Council.

SECTION 6. The Standing Committee on Publications shall consist of five Active or Honorary Members who shall serve a two year term concurrent with the Editor and who shall be appointed by the Editor. The committee shall have the duty of advising and assisting the Editor. The Editor shall appoint the chairman of this committee.

SECTION 7. The General Committee for the Annual Meeting to be held in a given year shall consist of a General Chairman and such additional persons as he may deem desirable. The General Chairman shall be appointed by the President with the concurrence of the Vice-President one or more years in advance of the Annual Meeting for which he is responsible and shall serve until the completion of all business related to the Annual Meeting. The other members of the General Committee, the Chairman and members of any Committees to handle specific phases of the Annual Meeting shall be appointed by the General Chairman. The General Committee for the Annual Meeting shall have the duty of arranging and holding the Annual Meeting at a time and place designated by the Executive Committee.

SECTION 8. The Standing Committee on Education shall consist of five persons appointed for one year by the President. The chairman shall be an Active or Honorary Member. The committee shall promote effective geophysical education.

SECTION 9. The Standing Committee on Student Membership shall consist of five persons appointed for one year by the President. The chairman shall be an Active or Honorary Member. The committee shall encourage the interest of students in geophysics and the Society.

SECTION 10. The Standing Committee on Distinguished Lectures shall consist of six persons appointed for three years by the President. The two senior members of the committee shall retire after the Annual Meeting. The chairman of the committee shall be appointed for one year by the President, and shall be an Active or Honorary Member. The committee shall obtain distinguished lecturers in geophysics and plan and supervise tours by these lecturers to the Local Sections of the Society and other participating organizations.

SECTION 11. The Standing Committee on Radio Facilities shall consist of from 5 to 15 Active or Honorary Members appointed for one year by the President. The committee shall, upon request from its chairman, determine the opinions of the members of the geophysical industry concerning matters pertaining to the use of radio in geophysics.

SECTION 12. The Standing Committee on Reviews shall consist of from 5 to 10 members who

need not be Active Members of the Society. The members and the chairman shall serve a two year term concurrent with the Editor and shall be appointed by the Editor. The committee shall prepare reviews of current geophysical literature for publication in GEOPHYSICS.

SECTION 13. The Standing Committee on Public Relations shall consist of a chairman, appointed for one year by the President, and such additional members, appointed for one year by the chairman, as he may deem desirable. The committee shall advise the officers and Council of the Society concerning matters pertaining to public relations, shall recommend public relations policy, and shall carry out projects to promote good public relations.

SECTION 14. The Standing Committee on Publicity shall consist of a chairman, appointed for one year by the President, and such additional members, appointed for one year by the chairman, as he may deem desirable. The committee shall prepare and arrange for the distribution of suitable publicity material for the press, radio, and other appropriate media.

SECTION 15. The Standing Committee on Geophysical Activity shall consist of four or more Active or Honorary Members of the Society appointed for a term of one year by the President. The committee shall conduct an annual survey of geophysical activities throughout the world. This report shall be presented before the Society at its Annual Meeting and published in the January issue of GEOPHYSICS. It may be made available for publication in leading trade journals for release at the time of the annual meeting.

SECTION 16. The Standing Committee on Safety shall consist of a chairman, appointed for one year by the President, and such additional members, appointed for one year by the chairman, as he may deem desirable. The committee shall recommend safety policy and shall carry out projects to promote safety in geophysical operations.

TWENTY-SIXTH ANNUAL MEETING
ROOSEVELT HOTEL, NEW ORLEANS, LOUISIANA
OCTOBER 29–NOVEMBER 1, 1956

The Twenty-Sixth Annual Meeting of the Society of Exploration Geophysicists will be held in New Orleans, Louisiana, October 29 through November 1, 1956. The Southeastern Geophysical Society is host. All technical sessions will be held in the Roosevelt Hotel, the headquarters for the Meeting.

THE TECHNICAL PROGRAM

Sunday afternoon and Monday morning will be devoted to registration, exhibits and the renewal of old friendships. The opening session will be held Monday afternoon and the formal technical program will run through Thursday afternoon. There will be no night sessions so that the charms of "Old New Orleans" can be enjoyed by all.

FIELD TRIP

There is a field trip planned for Friday, November 2. Busses will leave New Orleans that morning for Grand Isle, Louisiana, and return that night. Several oil fields of interest will be passed along the route. A demonstration of a marsh shooting job will be seen as well as a helicopter gravity meter survey in the marsh. A seafood dinner will be served at Grand Isle, then boats will be boarded for a cruise to the offshore area for a demonstration of gravity and seismic offshore work and observation of offshore drilling rigs and producing methods. The cost of the trip is $18.00 and *an advance deposit of $6.00 is required*, which should be sent to George Morgan, Humble Oil & Refining Co., Box 626, New Orleans, Louisiana.

HOUSING

Hotel accommodations have been reserved for this meeting in the leading New Orleans hotels. Housing application forms were mailed to all members of the Society August 2, 1956. Additional copies may be obtained from the Business Office, Society of Exploration Geophysicists, Box 1536, Tulsa 1, Oklahoma.

CALENDAR OF MEETINGS

1956

October

1– 3 National Electronics Conference, Hotel Sherman, Chicago, Illinois

18–20 Optical Society of America, Lake Placid Club, Essex County, New York (S. S. Ballard, Scripps Institute of Oceanography, San Diego 25, California)

28– 1 Society of Exploration Geophysicists, 26th Annual Meeting, Roosevelt Hotel, New Orleans, Louisiana (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

November

8– 9 Pacific Coast Regional Meeting, Society of Exploration Geophysicists, Ambassador Hotel, Los Angeles, California (Thomas A. Roy, Box 193, Bakersfield, California)

12–15 American Petroleum Institute, 36th Annual Meeting, Conrad Hilton Hotel, Chicago, Illinois

15–17 Acoustical Society of America, Los Angeles, California (W. Waterfall, 57 E. 55th Street, New York 22, New York)

23–24 American Physical Society, Chicago, Illinois (K. K. Darrow, Columbia University, New York 27, New York)

December

12–14 European Association of Exploration Geophysicists, Milan, Italy (Dr. B. Baars, B.P.M., Carel Van Bylandtlaan 30, The Hague, Holland)

1957

February

24–28 AIME Annual Meeting, Roosevelt Hotel, New Orleans, Louisiana

March

1– 2 American Physical Society, University of Oklahoma, Norman, Oklahoma (K. K. Darrow, Columbia University, New York 27, New York)

April

1– 4 American Association of Petroleum Geologists 42nd Annual Meeting—and Society of Economic Paleontologists and Mineralogists 31st Annual Meeting, Kiel Auditorium and Jefferson Hotel, St. Louis, Missouri (E. W. Ellsworth, Box 979, Tulsa, Oklahoma)

September

3–14 International Union of Geodesy and Geophysics Eleventh General Assembly, Toronto, Ontario, Canada. (Dr. J. A. Jacobs, 49 St. George St., Toronto, Ontario, Canada)

November

10–15 Society of Exploration Geophysicists 27th Annual Meeting, Statler-Hilton Hotel, Dallas, Texas (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

1958

October

13–16 Society of Exploration Geophysicists, 28th Annual Meeting, San Antonio, Texas

July 1, 1957 to December 31, 1958

International Geophysical Year. (Worldwide) vide GEOPHYSICS, v. 21, p. 257–259, and v. 21, p. 681–690.

THE INDEX

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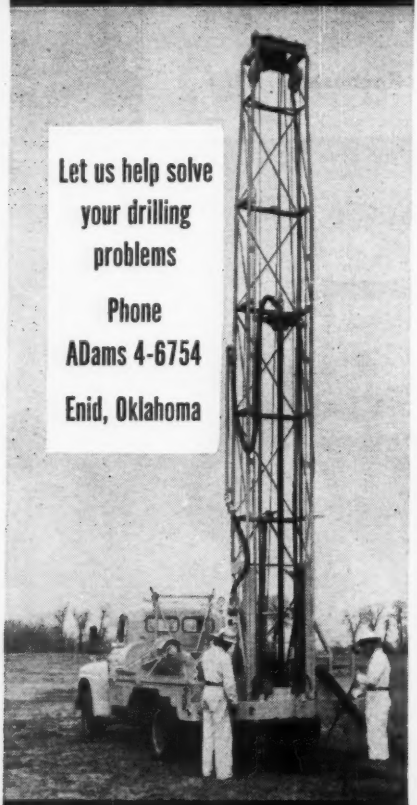

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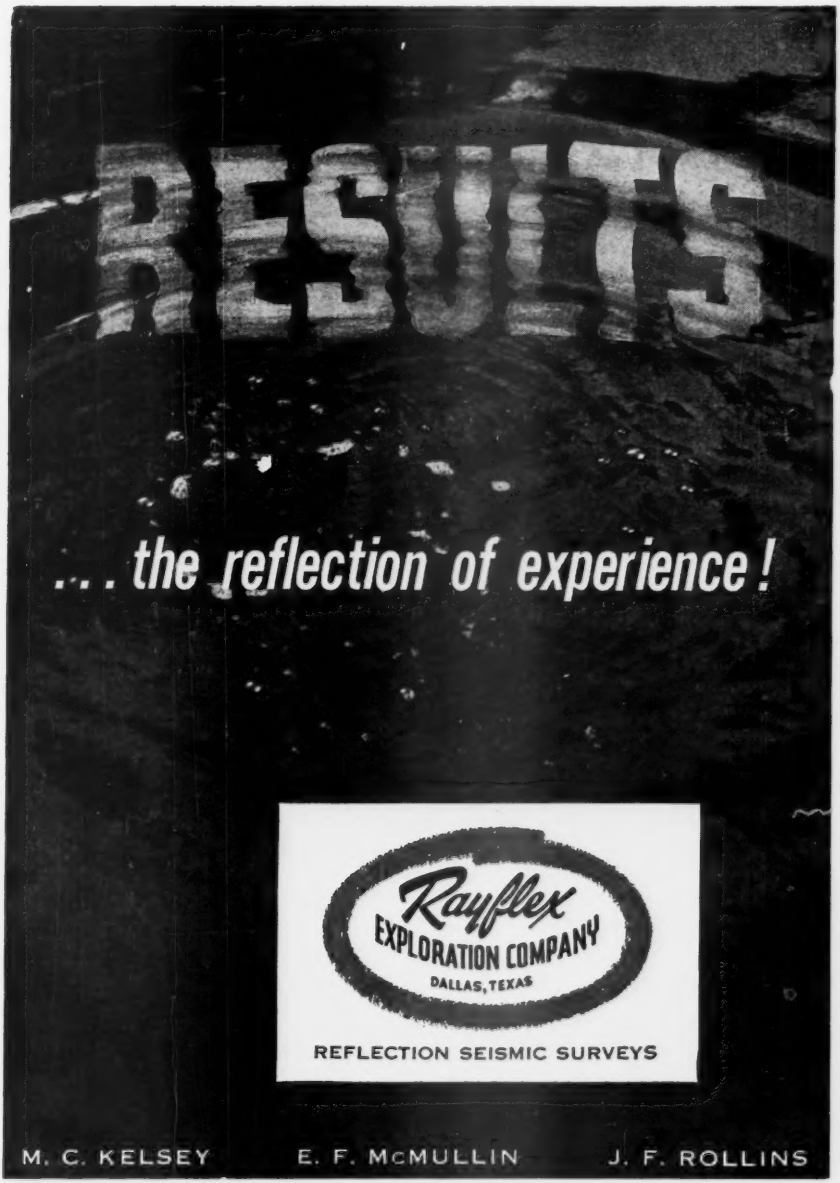
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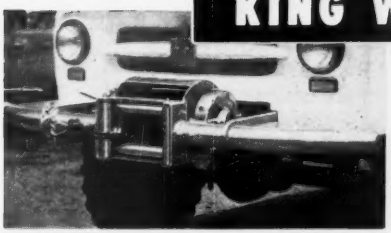

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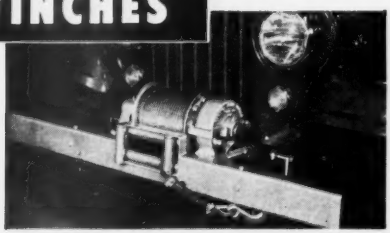

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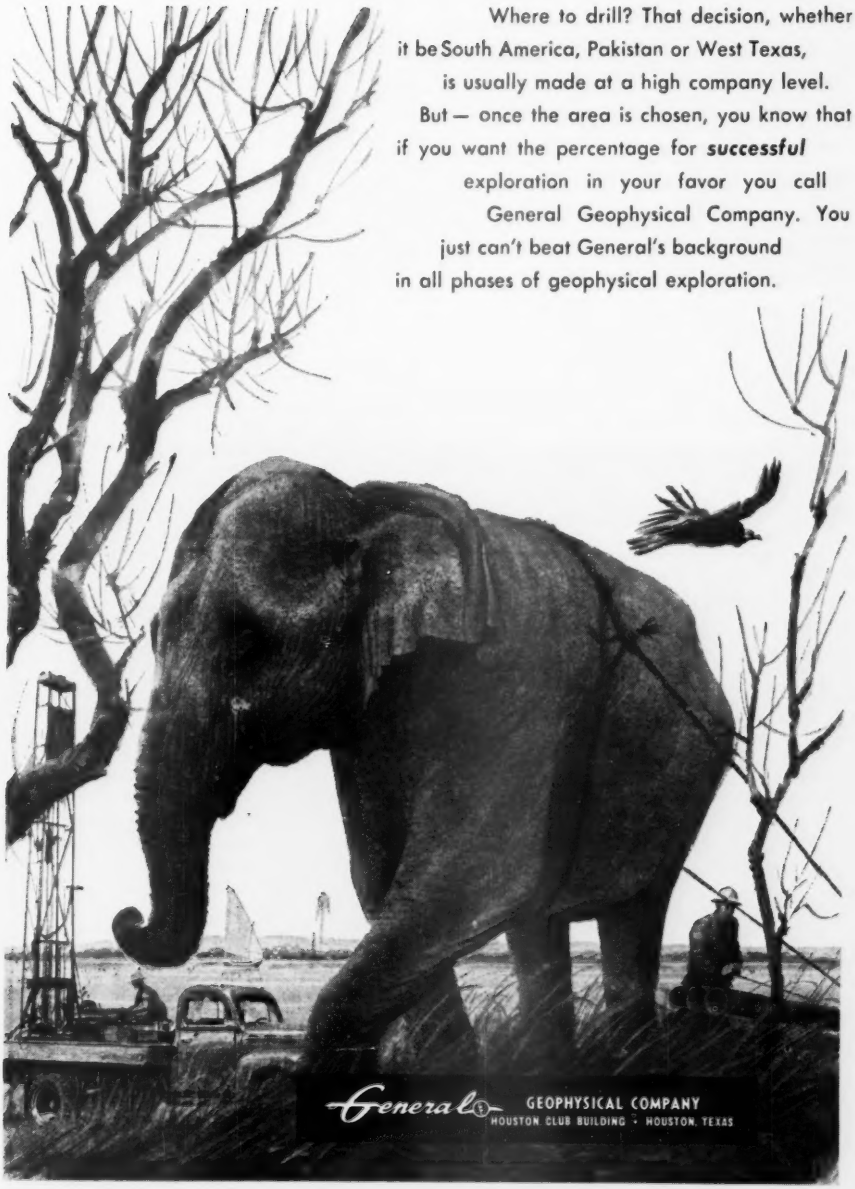

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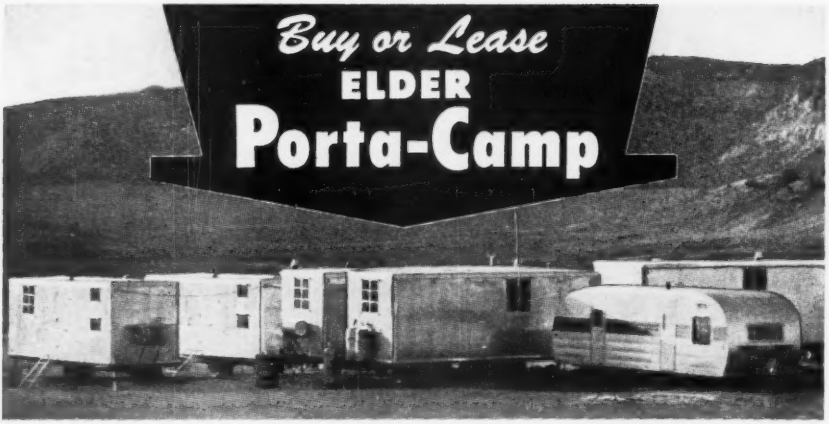

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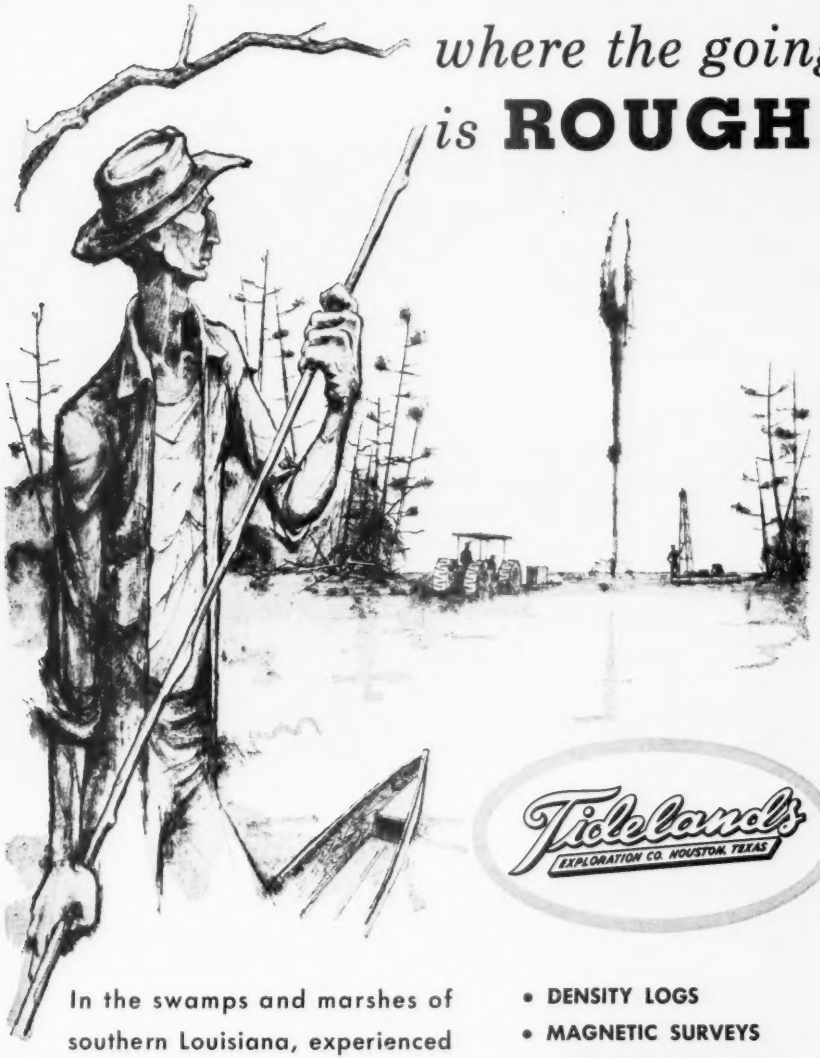

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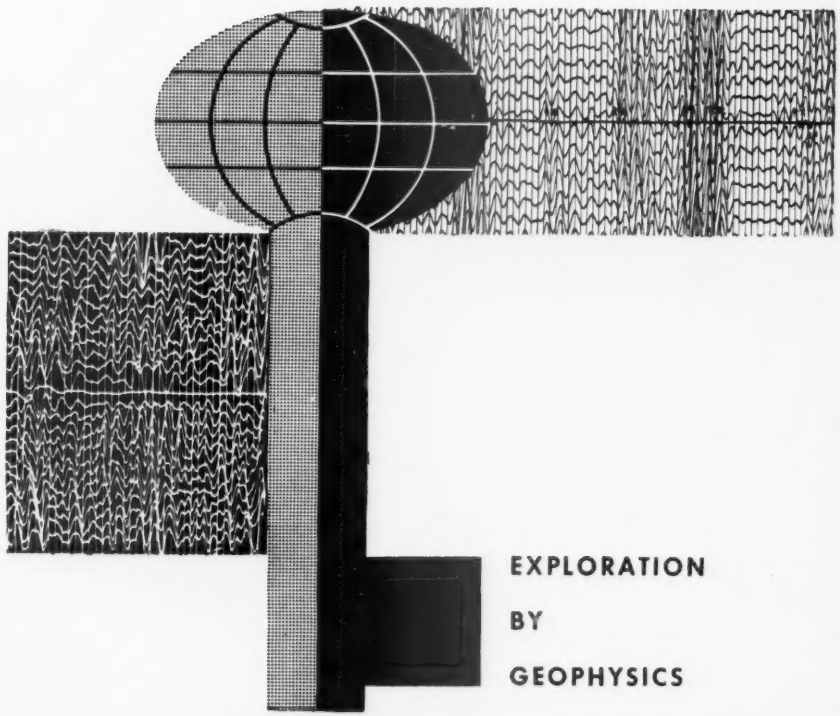

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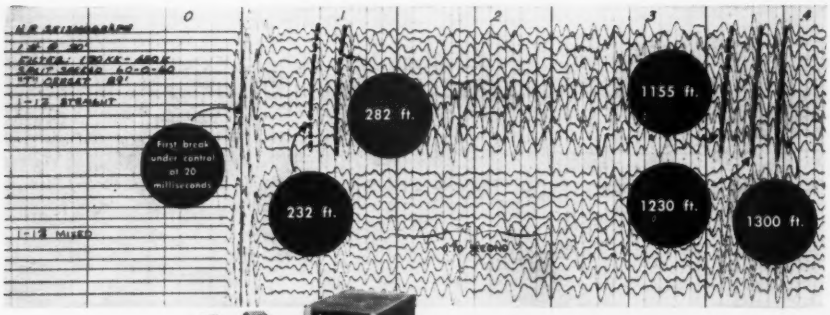

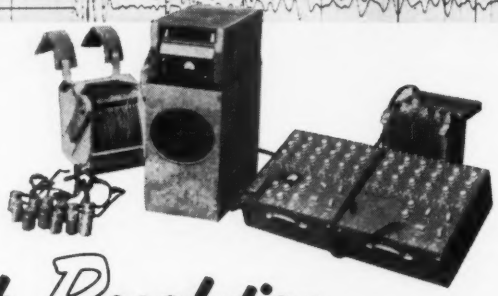

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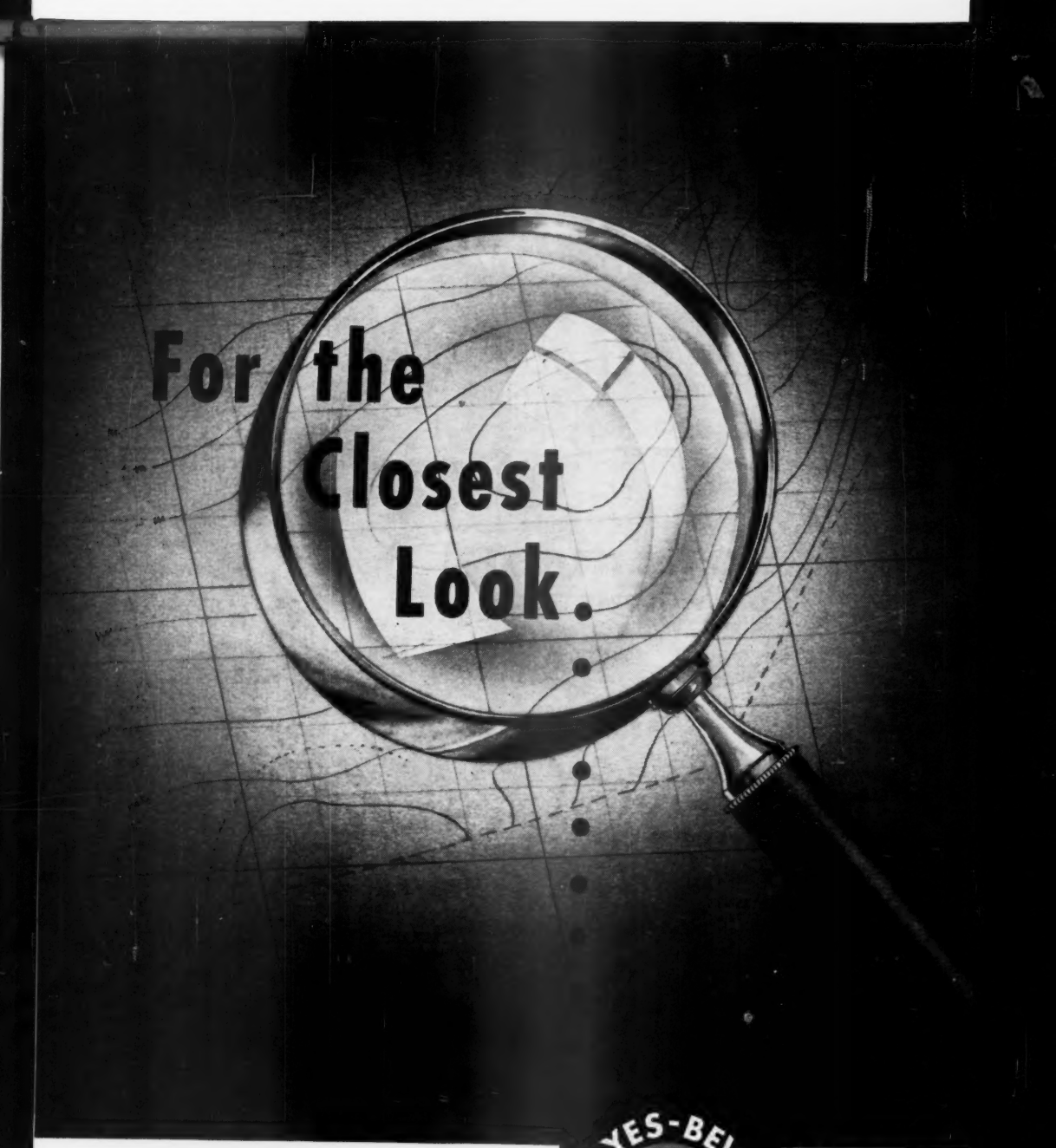

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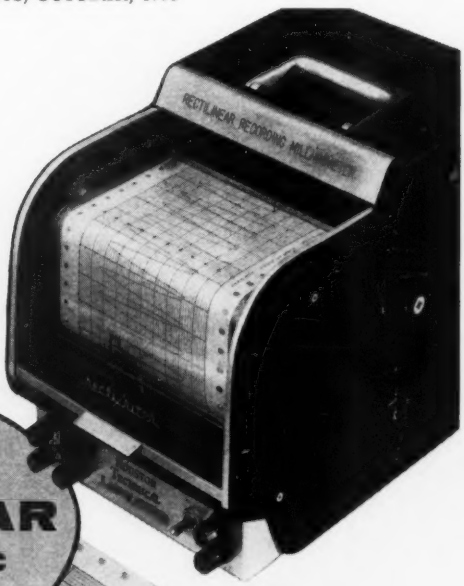

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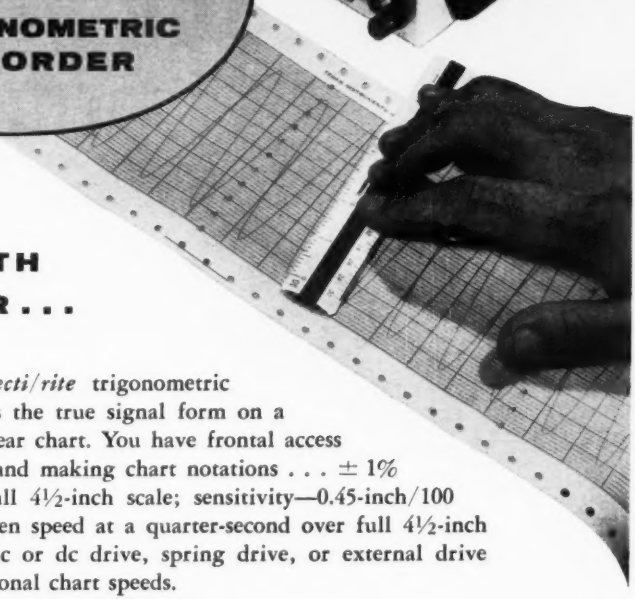

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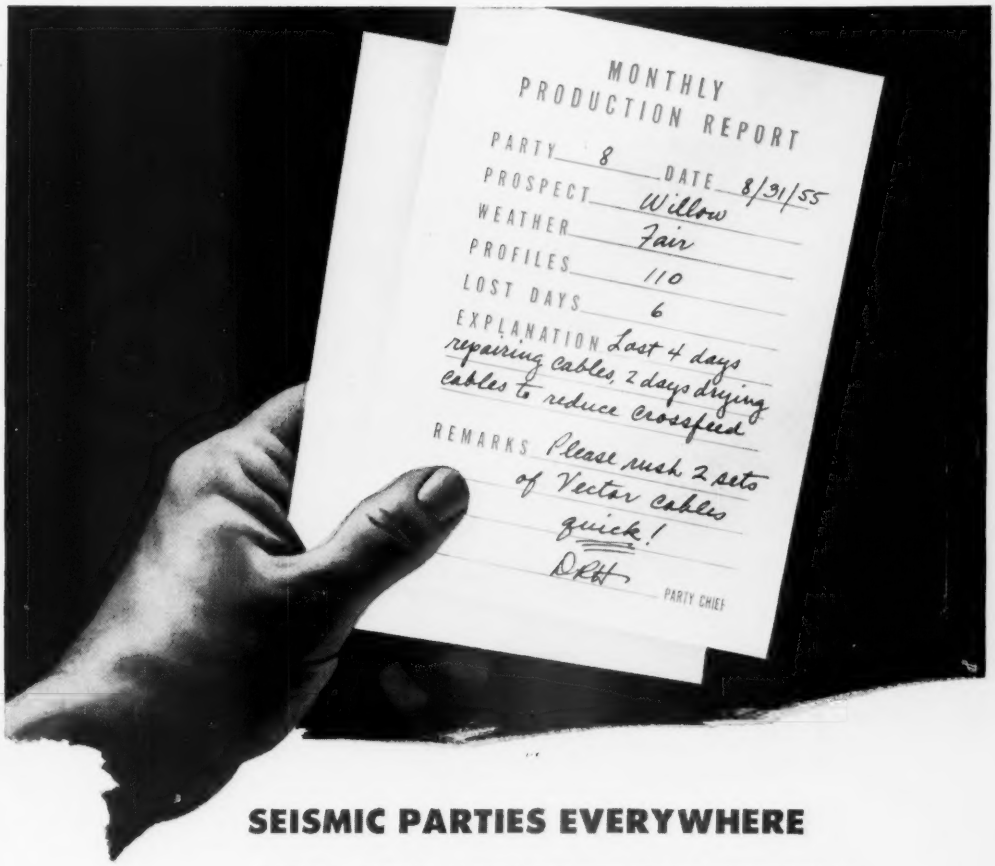
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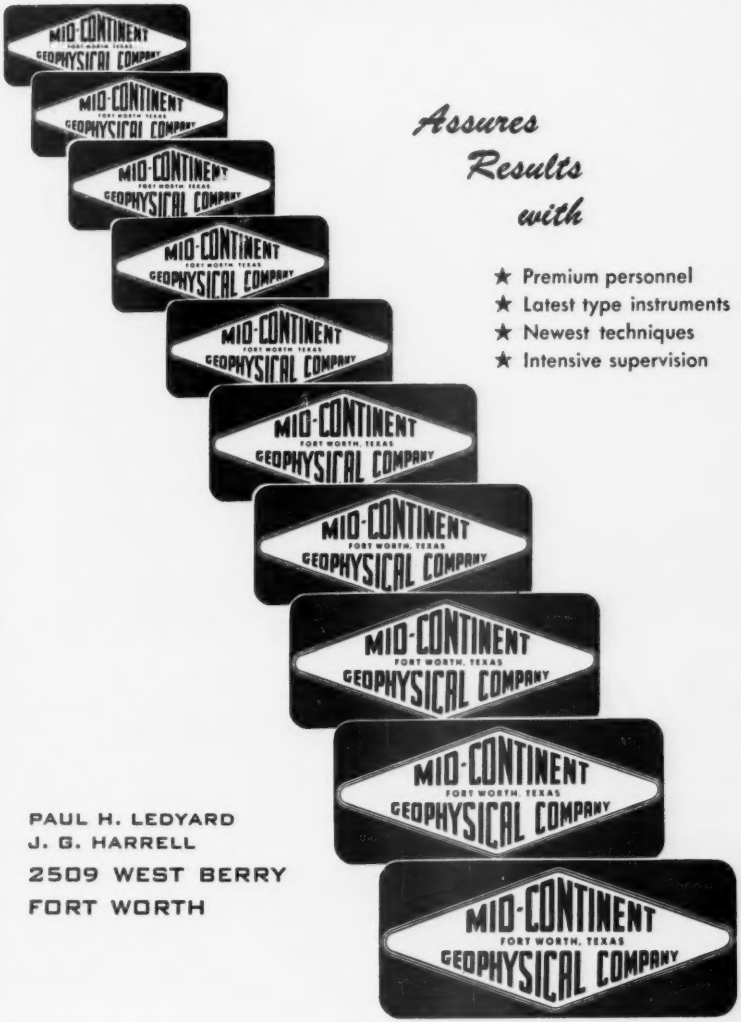

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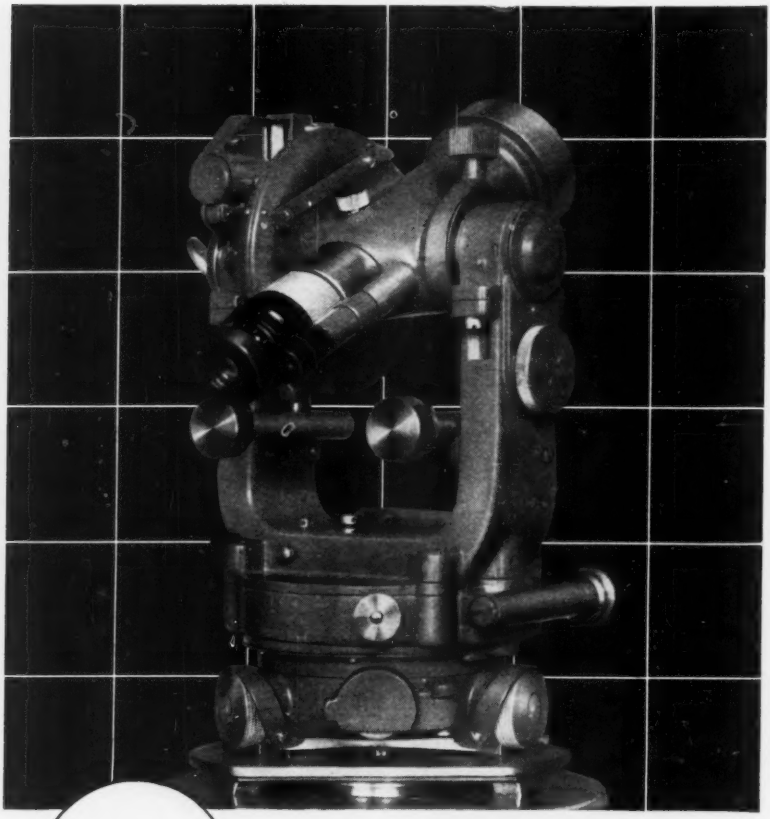

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Write for respective bulletins—
S-309 for the 7000 B, and S-313 for the RS-8U.

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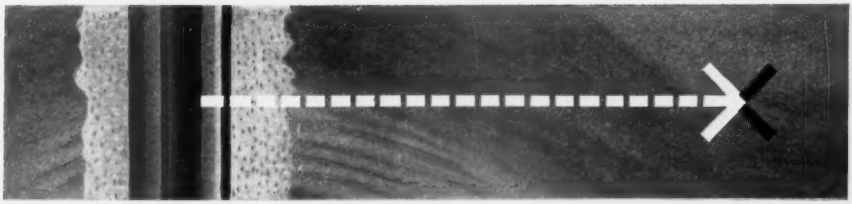

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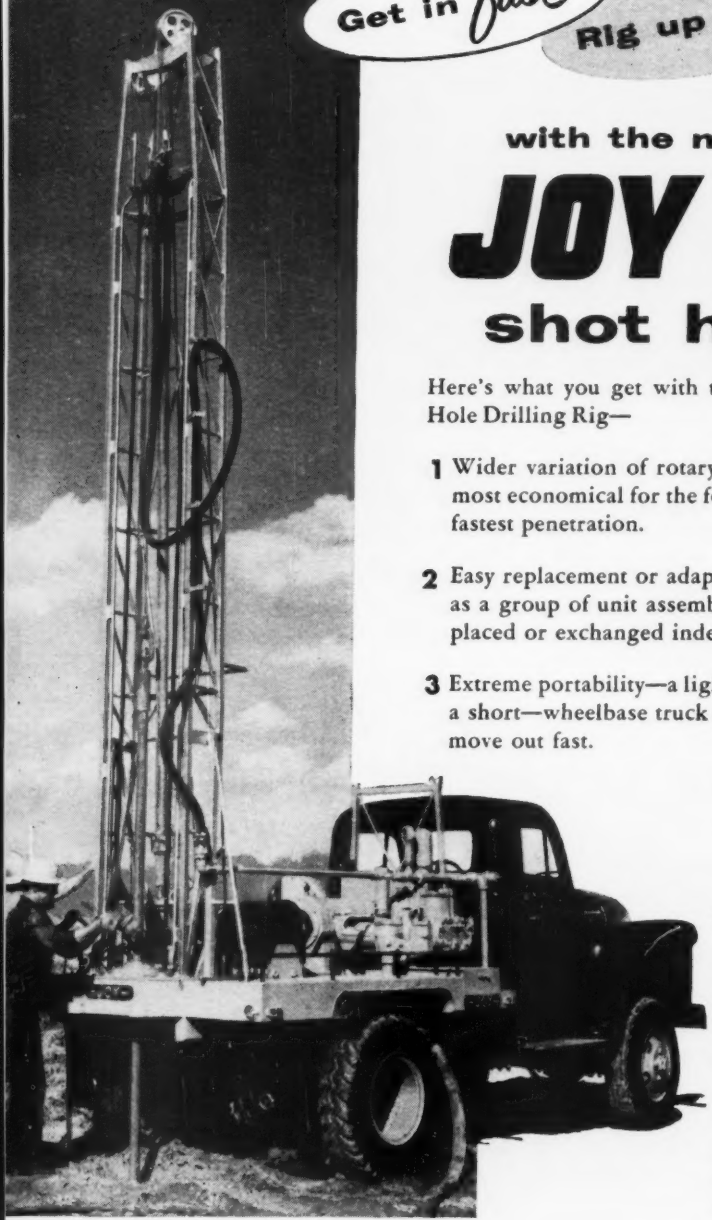

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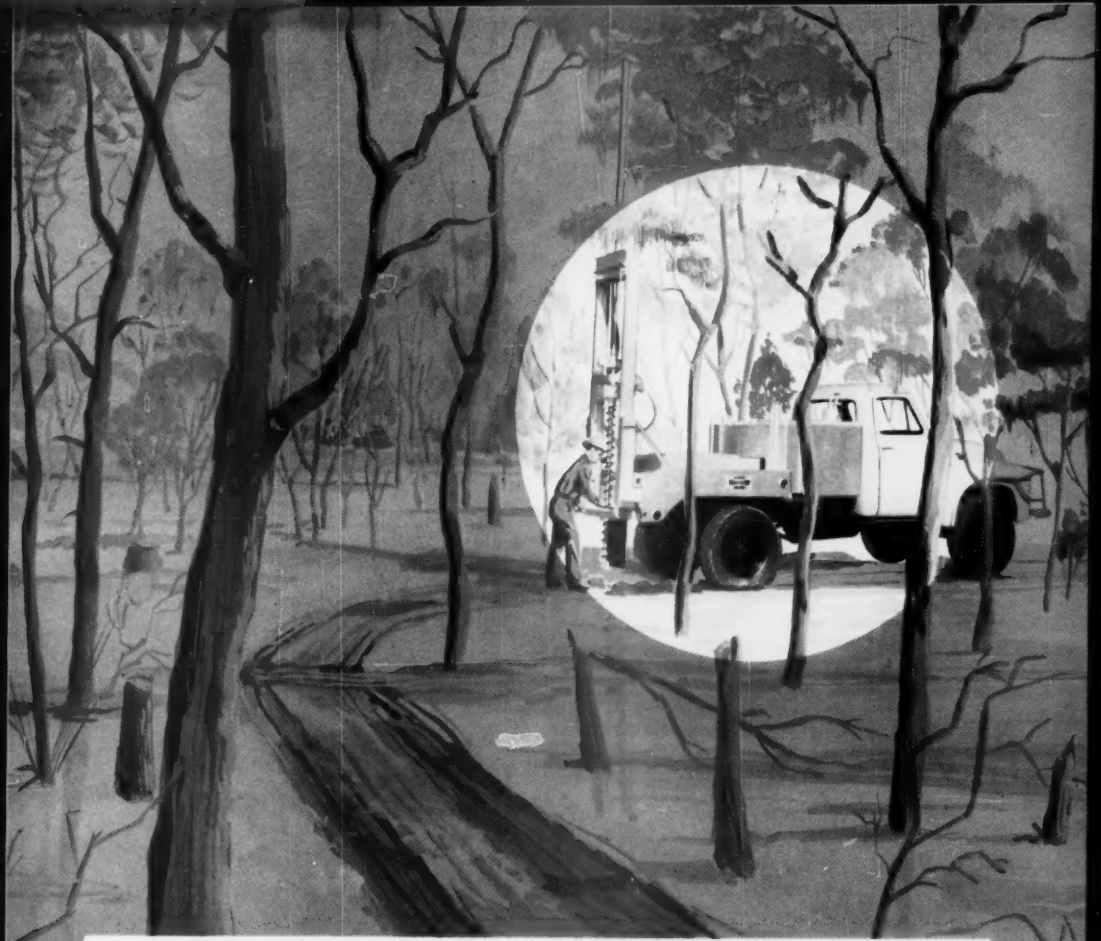

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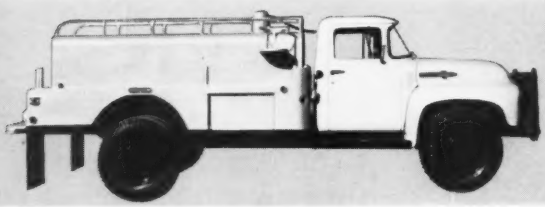

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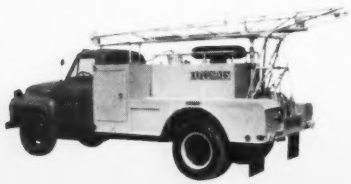

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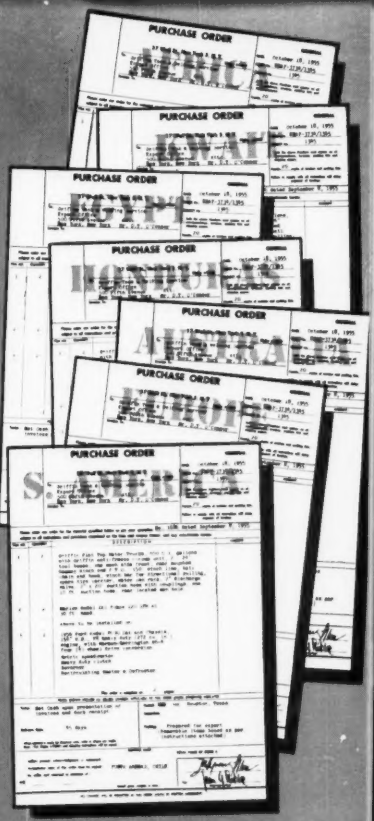

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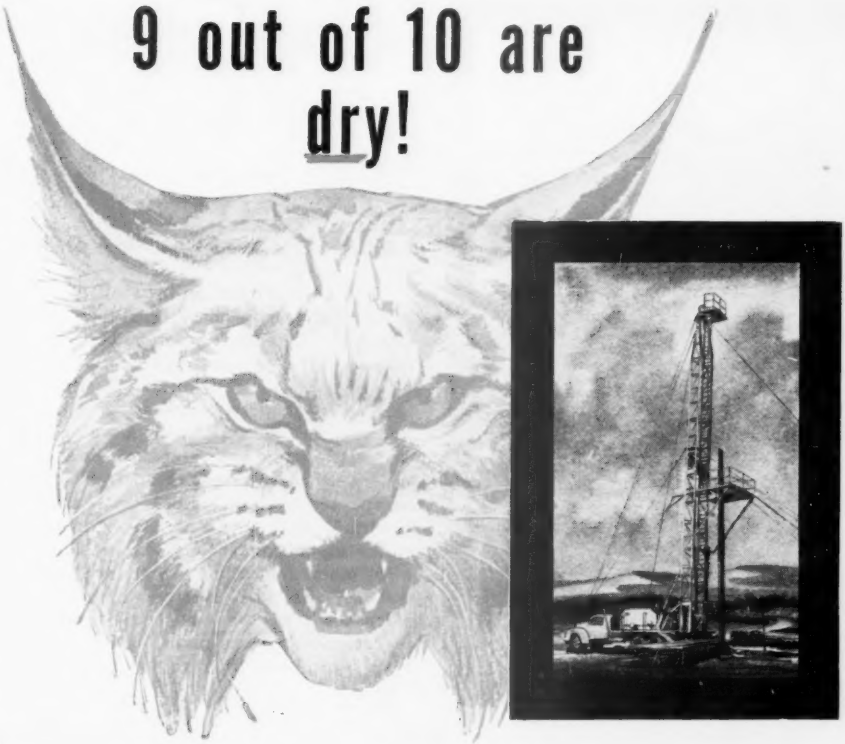

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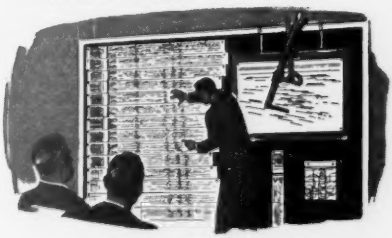
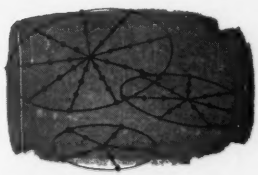


INTERPRETATION



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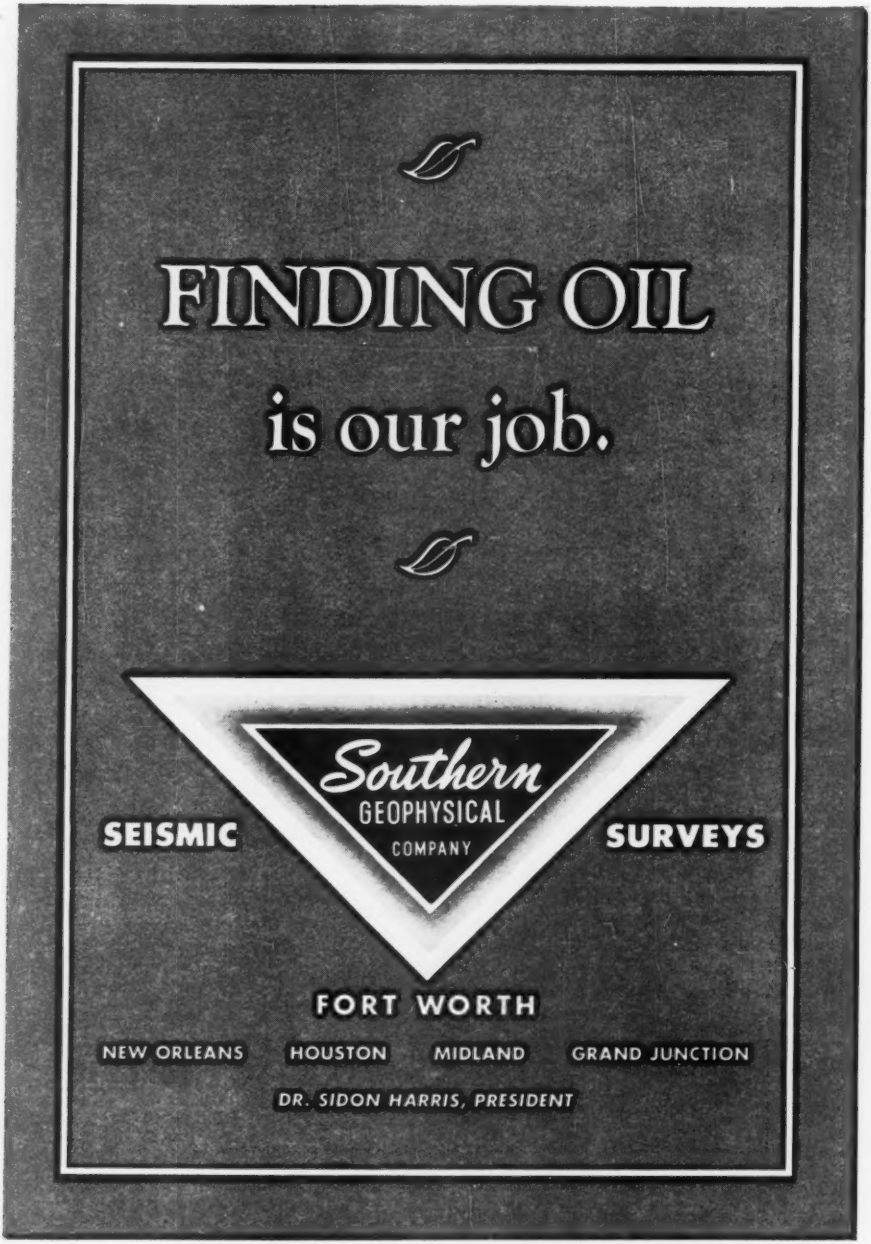
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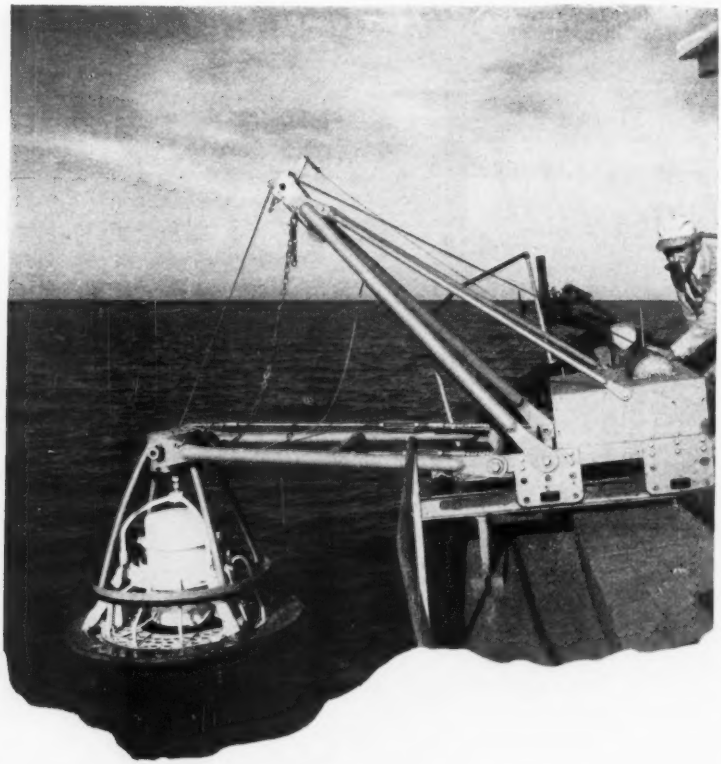

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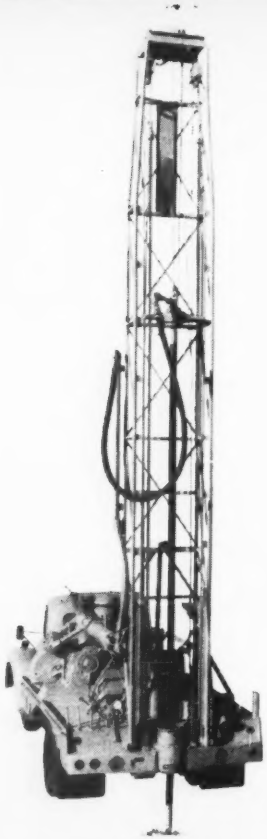

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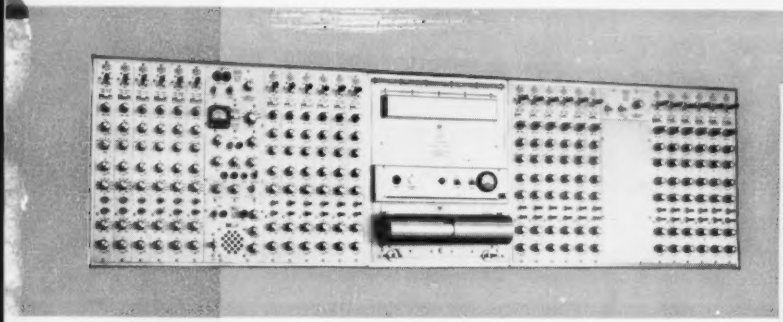

G-33 Full Spectrum
SEISMOGRAPH SYSTEM

SIE GA-33 Geophysical Amplifiers installed in an SIE G Series Seismograph System result in the widest range of recording applications ever offered the geophysical industry. In this small package are combined facilities for recording Refraction, Reflection, and High-Frequency seismic records . . . allowing the petroleum geophysicist to cover the entire seismic spectrum from 4 to 600 cycles-per-second with just one instrument.

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ESSENTIAL TO A COMPLETE GEOPHYSICAL PROGRAM

Although SIE G-33 equipment exceeds any other seismograph in its capabilities and range of applications, it occupies only half the space required by many conventional single purpose instruments. With adaptability to every seismic exploration method, outstanding operating flexibility, and maximum field utility in terms of size and weight, the G-33 Full-Spectrum Seismograph System meets every requirement of modern exploration programs.

The GA-33 Geophysical Amplifier features Full-Spectrum filtering, variable AGC time-constants, and extremely low distortion (less than 1%). Its wide range is especially useful in magnetic recording applications, while plug-in construction permits simple installation and easy maintenance.

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In magnetic recording instrumentation as in conventional seismograph manufacture SIE equipment continues to set,

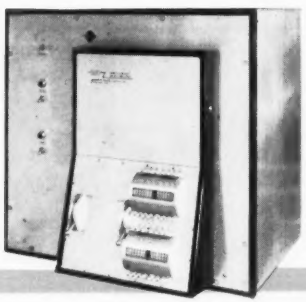
The Standard of the Industry

MR-4 MAGNETIC RECORDER

. . . features outstanding versatility and reliability. Signal-to-noise ratio in excess of 60 db, wide frequency range, and extremely low distortion suit the MR-4 for every field recording application.

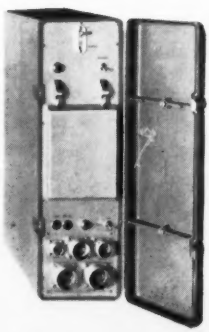
MR-5 MAGNETIC RECORDER

. . . can be used for more complex field recording, and is especially useful in laboratory analysis. Twin tape transport and individual head positioning controls allow recordings to be composited for noise integration and other interpretation techniques.



PMR-6 PORTABLE MAGNETIC RECORDER

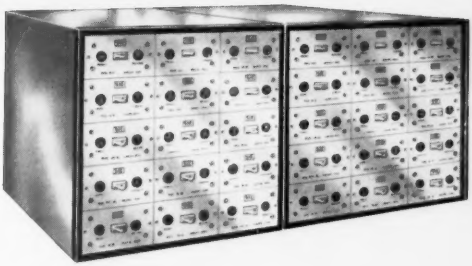
. . . can be used in areas completely inaccessible to vehicle mounted systems. Weighing only 43 pounds, the PMR-6 uses the same recording tape as the MR-4 and MR-5 and is easily carried by one man.



and LABORATORY ANALYSIS SYSTEMS

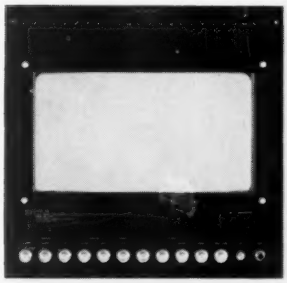
SIE auxiliary equipment for magnetic recording includes specially designed units and modifications for various field and laboratory techniques. Direct viewing equipment which allows records to be examined in the field with MR-4 and MR-5 Recorders, is one example. Recorders are available with or without frequency modulation equipment; the noise reducing SIE Length-Time Servo System; and moveable recording heads, thus permitting the selection of a system tailor made for every application at lower cost.

In the laboratory, the SIE Normal Move-Out Remover is one example of the specialized analysis equipment available. Development and research on other magnetic recording devices is a continuous process at SIE. When planning any phase of a wide-band instrumentation program, be sure to call for information on the latest SIE developments.



MODULATOR — DEMODULATORS

. . . for frequency modulation recording are housed in two cases for vehicle installation. Using the SIE Slope Modulator which provides an extremely high deviation ratio, the Units feature very low distortion—less than 1%.



MO MULTI-CHANNEL OSCILLOSCOPE

. . . allows laboratory presentation of an entire magnetic recording. Twenty-four channels are portrayed with timing lines, thus permitting records to be examined rapidly during interpretation and when compositing and filtering.

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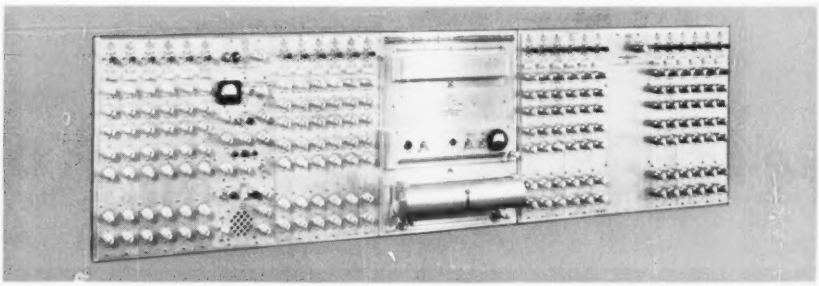
G-22A

SEISMOGRAPH SYSTEM



for high-production Operations

FREQUENCY RESPONSE: Within 3 db from 10 to 500 cps. Filtering as specified.

LOW DISTORTION: Less than 1% from 10 to 500 cps at 0.1 volt input.

AGC CONTROL RANGE: 0.5 microvolt to 0.1 volt input. (Three time-constants selected from front panel.)

GAIN CONTROL CIRCUITS: AGC, Expander, or simultaneous AGC-Expander operation.

RECORD PRESENTATION: Single record. Dual output. Dual record.

- First-Arrivals Unfiltered.
- Individual Channel Paralleling and Testing Switches.
- Simplified Controls.

Features essential to high-speed operation — available only on special order in many systems — are standard equipment in the G-22A.

New circuitry provides unmatched performance with all recording methods while simplifying matching and operating procedures.

AGC Time-Constants, mixing method and percentage, and type of record presentation can be selected from the front panel. Two attenuation rates on both high and low cut filters provide hundreds of filtering combinations.

From the new self-biased AGC circuit to the simplified control panel, the G-22A's "field engineered" design combines practical operation with high flexibility.

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The ability of the MicroLog to indicate porous zones and accurately define thin beds has been well established. The addition of the Caliper to the MicroLog provides other valuable information to determine casing and packer points, cement volumes and mud cake thickness, and it aids materially in better log interpretation.

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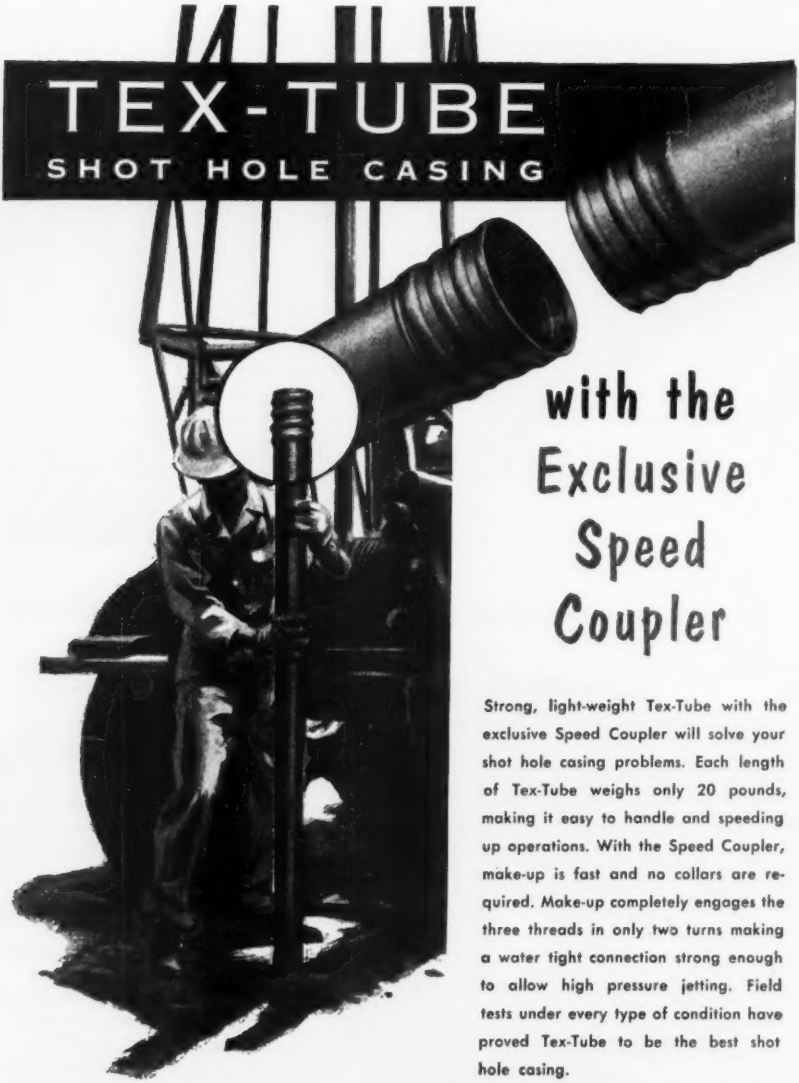
See your local Schlumberger engineer about this new service.

TEX-TUBE

SHOT HOLE CASING



with the Exclusive Speed Coupler

Strong, light-weight Tex-Tube with the exclusive Speed Coupler will solve your shot hole casing problems. Each length of Tex-Tube weighs only 20 pounds, making it easy to handle and speeding up operations. With the Speed Coupler, make-up is fast and no collars are required. Make-up completely engages the three threads in only two turns making a water tight connection strong enough to allow high pressure jetting. Field tests under every type of condition have proved Tex-Tube to be the best shot hole casing.

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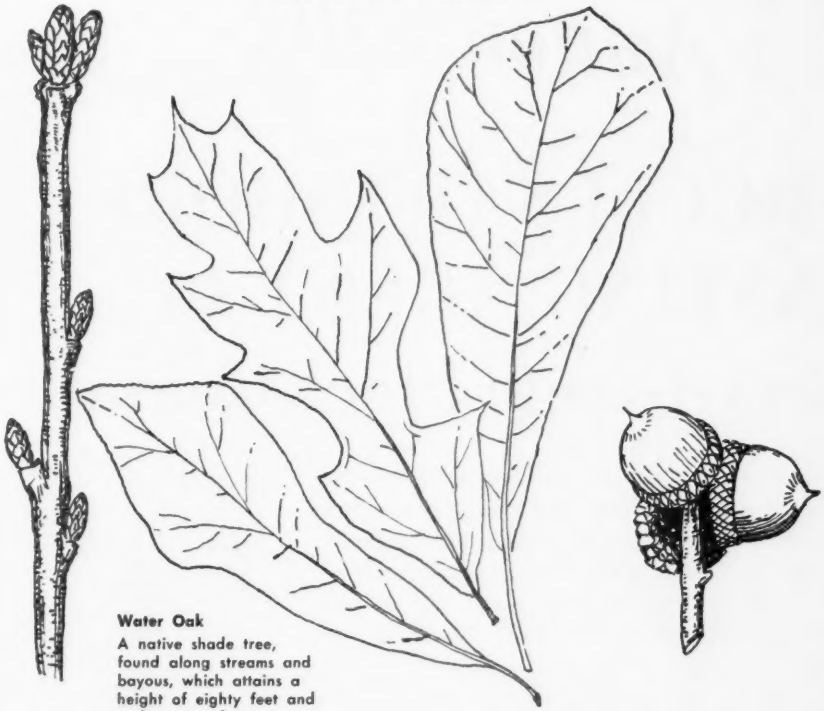

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Designed in the Hercules Research Center after careful study of actual offshore requirements, these new, improved steel containers meet all prospecting requirements included in reflection and refraction shooting.

Hercules representatives welcome the opportunity to discuss with you how Vibronite-B packed in these modern containers can assist in your seismic work.

Technical Data

Vibronite-B is packed in distinctive, light blue containers of heavy-gauge steel to withstand transportation, handling, and storage conditions, and to prevent water and moisture penetration. They have a density greater than salt water, which eliminates all possibility of floating charges. These completely new containers are also equipped with large bails and recessed ends to facilitate loading and unloading in the holds of boats, and to provide convenient handling by shooting crews. Hercules Vibronite-B is now available in five container sizes: 8 inches by 50 pounds; 8 inches by 40 pounds; 5½ inches by 25 pounds; 4½ inches by 16⅔ pounds; and 4½ inches by 10 pounds.

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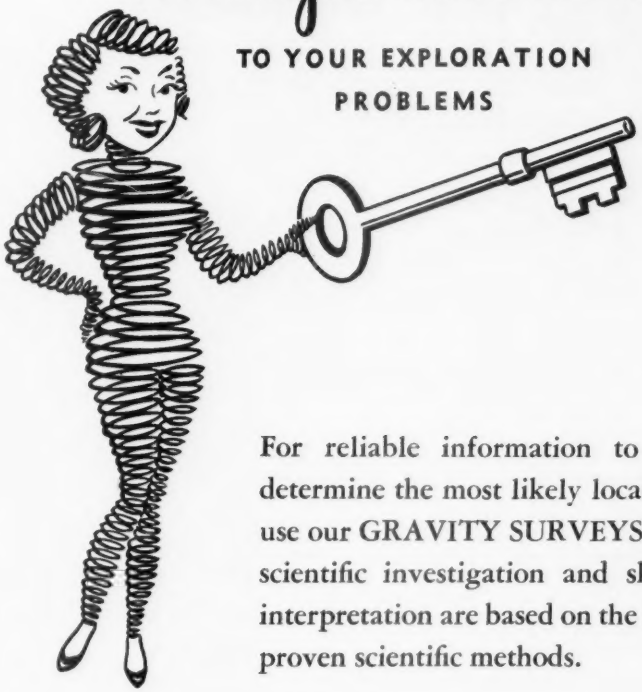

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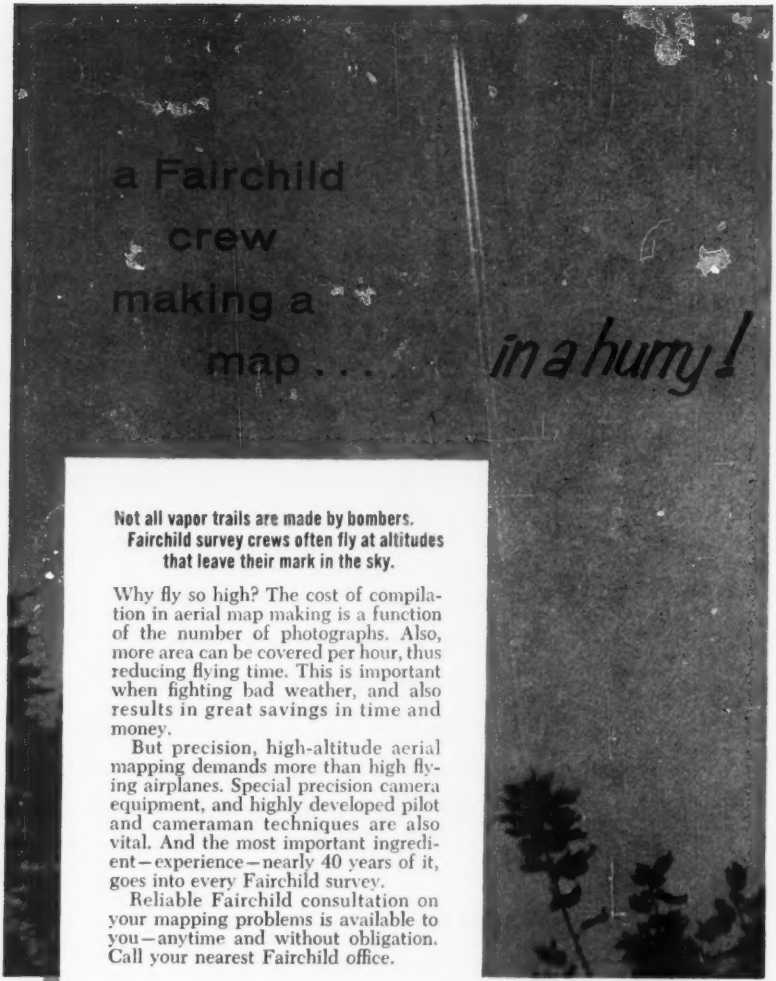

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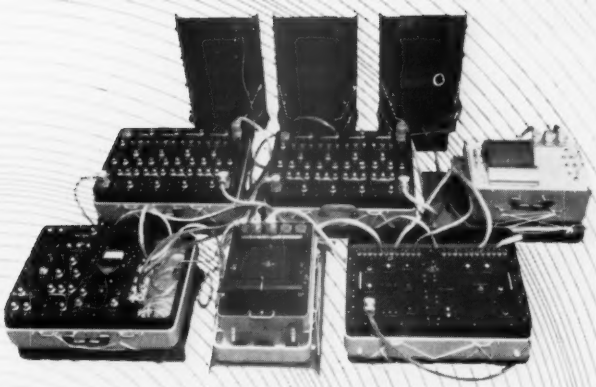


IMI

SEISMIC MAGNETIC RECORDING SYSTEM

This system, designed for multi-purpose applications, may be used as a conventional reflection seismograph, as a high-frequency reflection seismograph and also as a refraction seismograph.

It is a versatile system featuring portability, and the capacity to handle a wide frequency range of signals with minimum distortion.

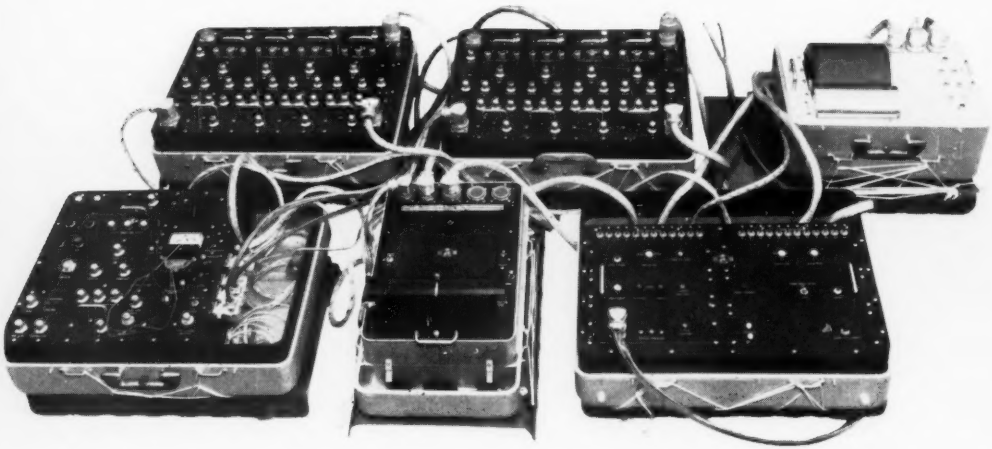
The self-contained magnetic recording equipment of the IMI may be used either in conjunction with a wide variety of filters, or to record directly wide-band seismic signals monitored by a photographic camera. These wide-band seismic signals may then be reproduced through amplifiers with any desired filters, and recorded on standard photographic paper.

Seismograph Service Corporation TULSA

IMI

SEISMIC MAGNETIC RECORDING SYSTEM

SSC's versatile IMI System consists of two IMI-150 Amplifier Cases, one IMI-250 Power Case, one CMH-100 Magnetic Recorder, one IMI-200 Power Case, and one CFA Camera. The cases are made of light-weight aluminum and may be truck-mounted or attached to pack boards for portable operation.
When magnetic recording is not required, the system may be operated without the CMH-100 Magnetic Recorder and the IMI-200 Power Case.



IMI Gives You Versatility *Plus!*

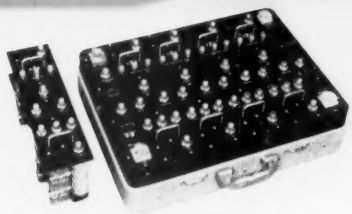
Flexibility—The IMI equipment has been designed to provide maximum flexibility with a minimum of circuit complexity. The instruments may be used as a conventional reflection seismograph, as a high-frequency reflection seismograph and also as a refraction seismograph. In any of these applications the magnetic recording system may be used separately. This system is one widely accepted by the seismic industry. A 24-trace mixed and a 24-trace unmixed record can be taken from the same shot on the 50-trace camera.

Portability—IMI units are contained in strong, light-weight aluminum cases which can be attached to pack-boards. These units can be quickly truck mounted.

High Fidelity—The amplifiers have a wide frequency range, 3.5 to 520 cycles per second, and can record input signals up to 0.3 volts with low distortion.

Multi-Climate Use—All units of the IMI are weather-proofed, for use in climates ranging from the humid tropics to the arctic cold.

Low Power Requirements—Only three 12-volt batteries mounted on pack-boards are required to furnish maximum power requirements.



AAD AMPLIFIER IN IMI-150 CASE

The IMI-150 Amplifier Case contains four amplifier chassis, function selector circuits, and circuits for testing geophones and operating voltages. The amplifiers are assembled with three channels per chassis which permits the ganging of several switches. The resulting reduction in the number of front-panel controls conserve space and simplifies operation. Amplifiers may be removed from the case for dynamic testing without disconnecting them.

GAIN.—From the input terminals to the output plate the gain is 120 db. The amplifiers have individual GAIN controls with a range of 30 db. Eighty db. of SUPPRESSION is provided, variable in twelve steps, and the suppression release RATE is variable in six steps. The master FINAL GAIN control has a range of 30 db. AMPLITUDE controls, with a range of 6 db., are provided to trim the individual channels.

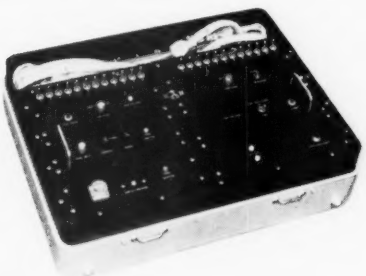
AVC.—The AVC has a threshold sensitivity of 0.8 microvolt and a range of 120 db. for a 6 db. increase in output. Four AVC speeds, Shallow Reflection, Short, Regular, and Long, are provided on each amplifier.

FILTERING.—The High-Pass filter has slopes of 20 and 37 db./octave, with cut-off frequencies of 29, 40, 58, 78 and 105 cps. In the R position, cut-offs of 3.5 and 18 cps are provided. The Low-Pass filter has slopes of 18 and 44 db./octave, with cut-off frequencies of 48, 66, 100, 140, and 190 cps. In the Out position, the cut-off frequency is 520 cps.

FIDELITY.—The AAD amplifier can handle a wide range of signal inputs up to 0.3 volts with low distortion.

The frequency range of the amplifier between 3-db. points is 3.5 to 520 cps.

For magnetic recording, without filters, the amplifier has less than 1 millisecond time shift at frequencies between 18 and 520 cps.

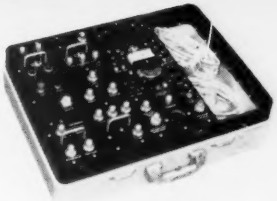


IMI-200 POWER CASE

This unit contains a fork-controlled power supply for the magnetic recorder, a 16-kc bias oscillator with its regulated power supply, a dual amplifier for recording and reproducing timing signals on the recorder, bias networks, and head-reversing switches.

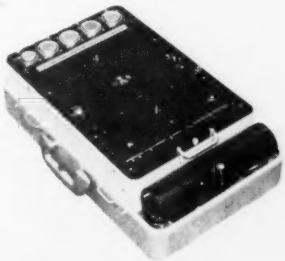
POWER REQUIREMENTS

Three 12-volt batteries are required for primary power. In portable operation these batteries are mounted in IMI-113 Battery Packs. The 12-volt current drain is as follows: Standby—36.7 amps, Recording—51.2 amps, and Reproducing—36.5 amps.



IMI-250 POWER CASE

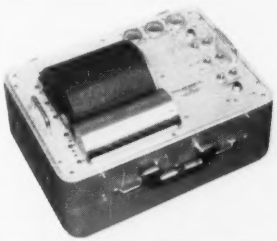
This unit includes power control circuits and regulated power supply for the amplifiers, test meter, voice amplifier, test oscillator, suppressor, vertical time amplifier, time break circuit, synthesized time break/vertical time for magnetic recording, and a spare amplifier. Storage space is provided for interconnecting cables.



CFA CAMERA

The CFA 10-inch camera is a 50-trace unit which is normally equipped with galvanometers of 150 cps natural frequency, damped to 0.7 critical; however, 500-cycle galvanometers are available. The timing unit is a fork-driven synchronous motor which places time lines on the record at 10-millisecond intervals, with the 50 and 100-millisecond lines accentuated. The recording paper is driven by a 12-volt, d-c motor which is controlled by a governor. A removable paper receiver is supplied for daylight operation.

The camera is normally equipped with a unidirectional, adjacent-channel mixer, which provides 24 single traces and 24 mixed traces on the same record. The two remaining galvanometers record a signal from the camera fork and a 50-cps signal from the recorder power supply. Other mixing circuits or dual amplitude circuits are available.



CMH-100 MAGNETIC RECORDER

The CMH-100 is a modified Techno TI-451 Recorder-Reproducer. It provides 26 channels on a 6⅜ inch plastic sheet, coated with iron oxide. Recording time is approximately six seconds at a drum speed of 3.6 in./sec. The drive motor is of the hysteresis-synchronous type, operating on 110 volts a-c at 50 cps.

Provisions are made to start the recorder with the RECORD switch on the CFA Camera and to synchronize shot firing with a predetermined drum position. Control switches and relays are included in the recorder case.

Twenty-four channels record wide-band seismic information. The two remaining channels record a synthesized time break/vertical time signal and a 50-cps signal from the recorder power supply.

IMI

BRIEF SPECIFICATIONS

AAD AMPLIFIER

Channels	24
Gain	120 db.
Frequency Range	3.5 to 520 cps
AVC Threshold	0.8 microvolt
AVC Range	120 db.
AVC Speeds	4
Suppression	80 db.
Suppression Release	6 rates
HP Filter	
Slopes	20 & 37 db./octave
Cut-offs	3.5, 18, 29, 40, 58, 78 & 105
LP Filter	
Slopes	18 & 44 db./octave
Cut-offs	48, 66, 100, 140, 190 & 520

CMH-100 MAGNETIC RECORDER

Channels	26
Recording Time	6 sec.
Drum Speed	3.6 in./sec.
Bias Frequency	16 kc.
Tape Width	6⅜ in.

CFA CAMERA

Galvanometers	50
Natural Freq.	150 cps.
Damping	0.7 critical
Timing Accuracy	± 0.5 ms.
Paper Speed	12 in./sec. normal
Paper Capacity	150 ft., 10 in. wide

DIMENSIONS AND WEIGHTS

UNIT	SIZE (INCHES)	WEIGHT
IMI-150 Amplifier Case	8 x 18 x 24	58 lbs.
IMI-250 Power Case	8 x 18 x 24	52½ lbs.
CMH-100 Recorder	10½ x 13 x 18	38½ lbs.
IMI-200 Power Case	8 x 18 x 24	62 lbs.
CFA Camera	6½ x 13 x 21	38 lbs.
IMI-113 Battery Pack	8 x 15 x 24	55 lbs.

CATALOG C-1

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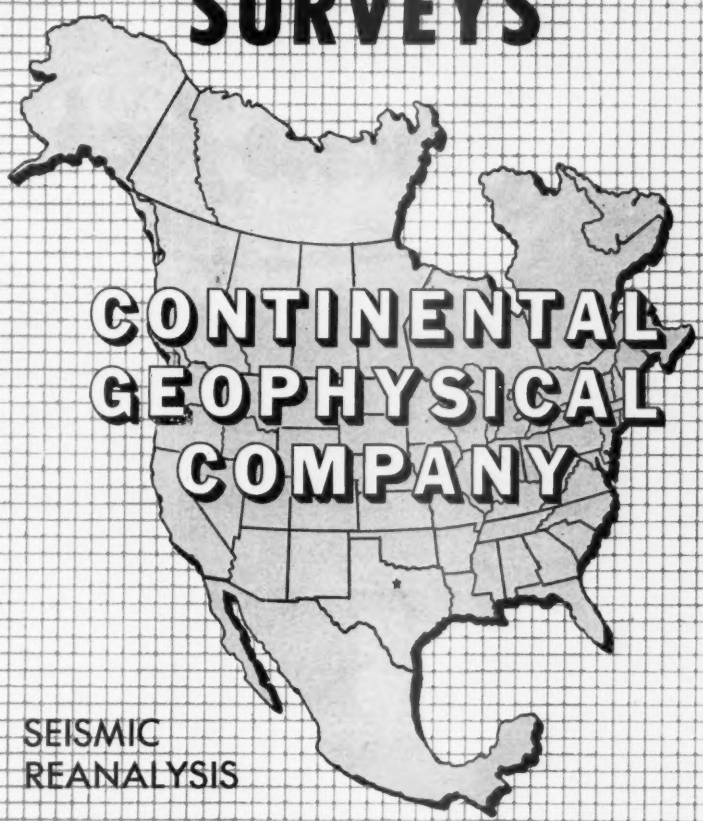

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MAGNETIC RECORDER

Model FR-1 24 Channel

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For the Geophysicist

Who wants to

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The FR-1 is a complete magnetic recording system utilizing pulse width modulation together with the latest concepts in geophysical amplifiers. The monitor record is obtained through an instantaneous dry process, precluding the need for dark room facilities.

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a Seismograph system

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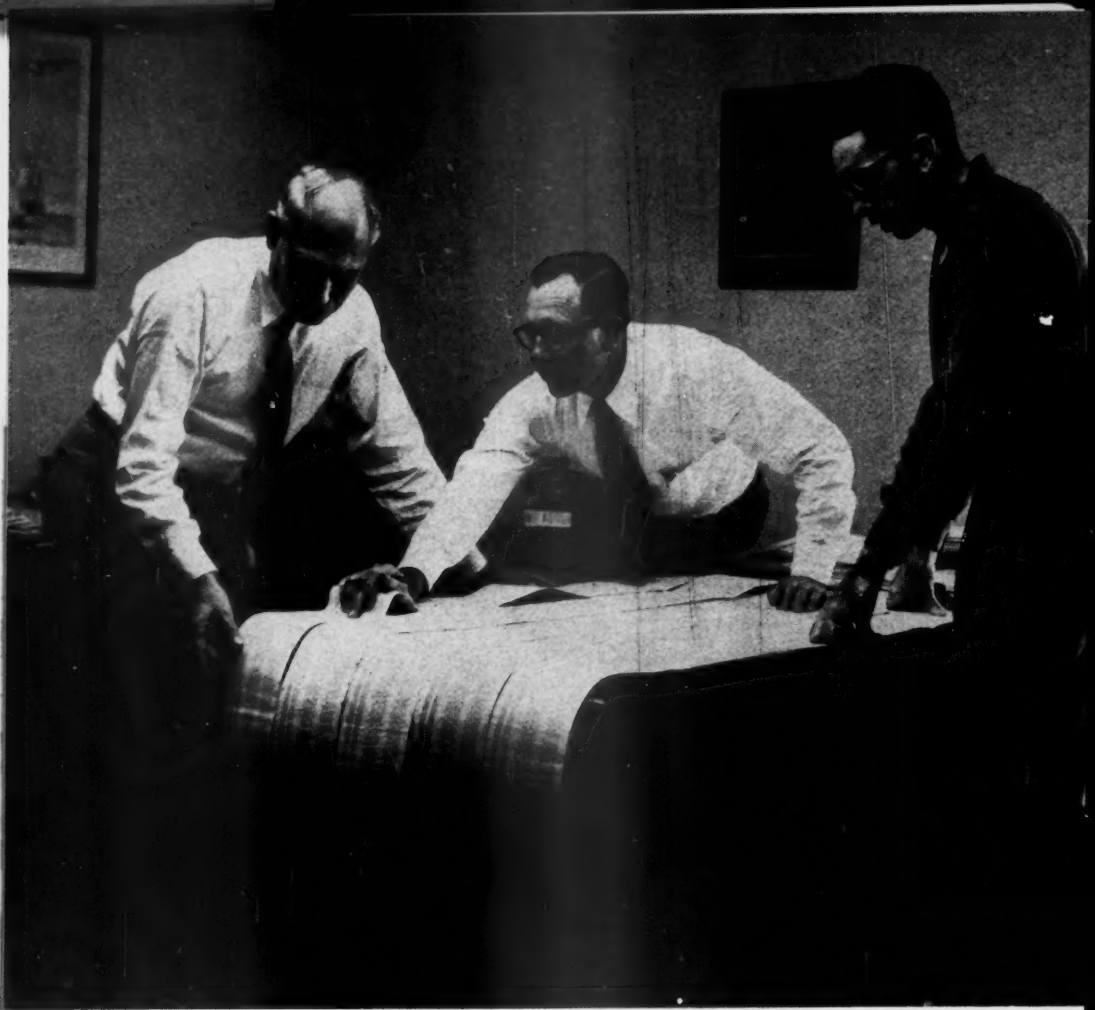

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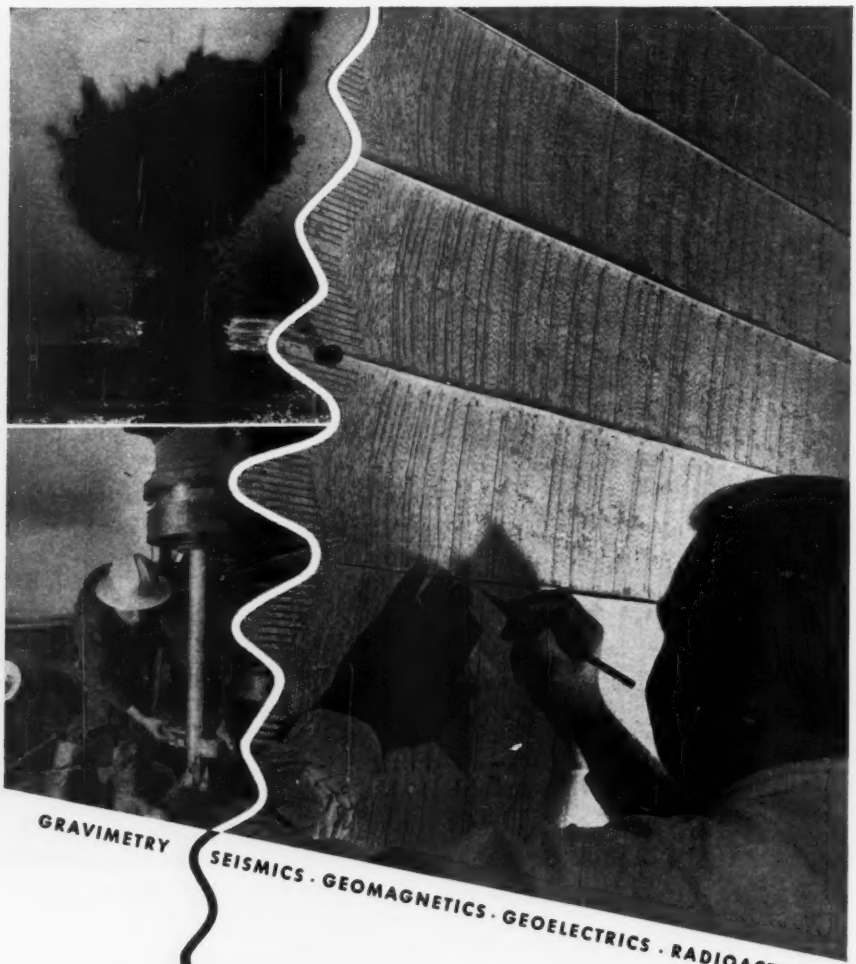

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TEXAS DIVISION

THE BRUSH COMPLETE MAGNETIC RECORDING AND ANALYZING SYSTEM

TEXAS DIVISION

BRUSH ELECTRONICS COMPANY

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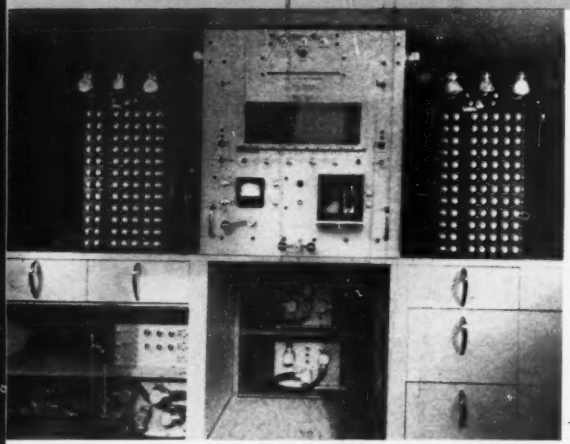
THE BRUSH COMPLETE MAGNETIC RECORDING AND ANALYZING SYSTEM



TWENTY-FOUR CHANNEL RECORDER MODEL TR-2 *Magnetic Recorder-Monitor flanked by twenty-four channels of Model AM-2 Amplifier Modulator units.*

BASIC SPECIFICATIONS

Signal to noise—56 db (rms) without noise cancelling.
62 db (rms) with noise cancelling.

Trace to trace timing accuracy—Plus or minus ½ millisecond.

Absolute timing accuracy—Plus or minus ½ millisecond.

Harmonic Distortion—Less than one percent *TOTAL*.

Phase Distortion—Less than one millisecond over 20-300 cps range.

Frequency Range—Five to 500 cps.

Recording Time—5.6 seconds.

Tape Width—Four inches.

Carrier Frequency—4,000 cps.

Maximum Modulation—Plus or minus fifty per cent (2,000 cps).

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The Brush Twenty-Four Channel Recorder, for truck or boat mounting, consists of:

MODEL TR-2 MAGNETIC RECORDER-MONITOR

- Twenty-eight channel tape on drum recorder.
- Galvanometer style viewing monitor system—for monitoring before and during shooting.
- Direct writing permanent record monitor system, with built-in seismic filters.
- 100 cps timing signal channel.
- Noise cancellation channel (optional use).
- Two information channels (uphole, time break).
- Twenty-four signal channels.
- Speed lock system for high positional stability.
- New rigid belt drive system for tight, smooth tape movement.

MODEL AM-2 AMPLIFIER-MODULATOR UNITS AND CONTROL PANEL

- Twenty-four channels of integral broad band seismic amplifier and frequency modulator.
- Variable soft filtering, for eliminating excessive ground roll or high frequency disturbance.
- Standard high quality seismic amplifier gain, AGC, suppression, line balance, and test features.
- Standard high quality seismic amplifier control panel with trip, suppression control, by-passed first breaks, and test features.

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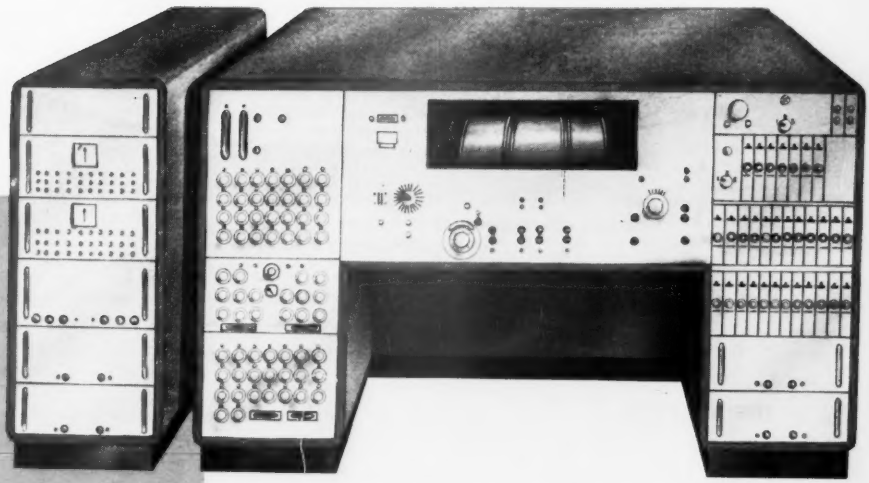

MODEL MRA-2 MAGNETIC RECORD ANALYZER —
for complete correction, compositing, reproducing, filtering, and mixing.

THE BRUSH MAGNETIC RECORD ANALYZER for central laboratory or field office use provides, as its end product, the visual photographic record of one or many field tapes—with these flexible features:

- Correcting.
- Compositing.
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The **MODEL MRA-1** inserts the constant weathering and elevation corrections. It provides time section photographic records with these constant corrections. It composites any number of tapes shot with the same spread and same shot hole (different depths). A broad selection of filtering and two types of mixing are available.

The **MODEL MRA-2** inserts the variable stepout corrections as well as the constant corrections. It provides either time section or depth section photographic records with all corrections inserted. It composites any number of tapes shot with the same spread and *different* shot hole locations and depths. A broad selection of filtering and two types of mixing are available.

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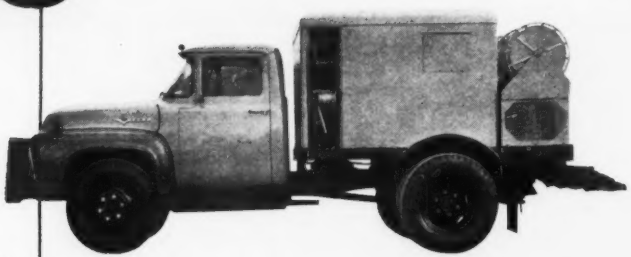
THE RECORDER with a new concept of tape drive—for the optimum in noise-free smoothness, absolute positional stability and timing accuracy, and precise, truck-to-truck uniformity.

THE ANALYZER for the flexible and time saving, automatic handling of the tape records. Correcting, Compositing, Filtering, Mixing, and play back in *time* or *depth*.

THE SYSTEM FM recording, self-checking servos, electrical computer elements chosen for optimum technical performance. Controls and layout operator—engineered for optimum labor saving performance.



BRUSH 6 ELECTRONICS

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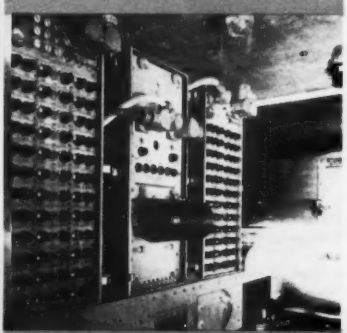
MODEL 521 DUAL PURPOSE SEISMOGRAPH SYSTEM



SUMMARY SPECIFICATIONS

The Model 521 Dual Purpose Seismograph System, consisting of one or two banks of twelve amplifier channels with one control panel each, and of one recording oscillograph, was designed for all types of geophysical operations. Emphasis was placed on ruggedness, long life with minimum maintenance, compactness, and portability. No individual package weighs more than fifty pounds. These units can be used in a light weight recording cab, on truck or boat, and then quickly dismounted for carrying by man.

In addition to the above, main features of the amplifier bank of twelve channels and one control panel are:

1. Fifty pounds weight.
2. 18½" height x 8½" width x 8" depth.
3. Power requirements—16 amps at 6 volts, 27 ma at 90 volts.
4. Input panel, test oscillator, and meter as part of unit.
5. Three selections of mixing.
6. Delay of mixing until after first breaks.
7. Trip on first, sixth, or twelfth trace.
8. Suppression decay.
9. AGC speed of 0.1 second or less, if desired.
10. Non-corrosive, completely water-tight, stainless steel case.
11. Unitized plug-in design to facilitate easy service or replacement.

Main features of the recording oscillograph (six inch, 25 trace recommended for highest degree of portability) are:

1. Thirty pounds weight.
2. 18½" height x 8½" width x 8" depth.
3. Power requirements—Standby— 7 amps at 6 volts.
   Operation—18 amps at 6 volts, 15 ma at 90 volts.
4. Clear visibility of galvanometer spots in daylight.
5. Two hundred feet paper capacity.
6. Record length control.
7. Governor controlled paper speed variable from ten inches to sixteen inches per second.
8. Built-in communication system with two stage amplifier.
9. 100 cps note on 25th trace for hunting check.
10. Non-corrosive, completely water-tight, stainless steel case.

The TICO Recording Oscillographs are available in models handling six-inch to ten-inch paper widths and with six to fifty traces.

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MODEL 321-MT PRESSURE DETECTOR

2½" x 6"

3 lbs. in Air

2¼ lbs. in Water

Operating Principle ..... Piezoelectric ceramic with matching transformer.

Ruggedness ..... Will survive at least 20 7-ft. drops to concrete floor and at least 200 lb./in.^{2} pressure.

Sensitivity ..... 0.4 volts/atmosphere—0.4 microvolts/dyne/cm^2.

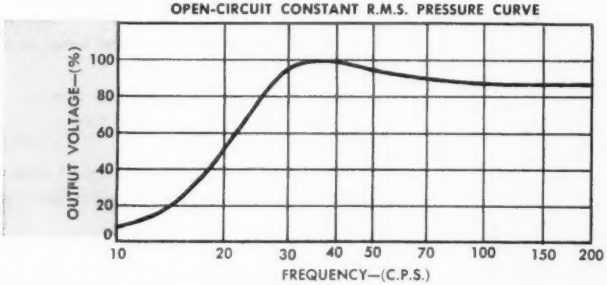
Frequency ..... Natural resonance of 22 cps.

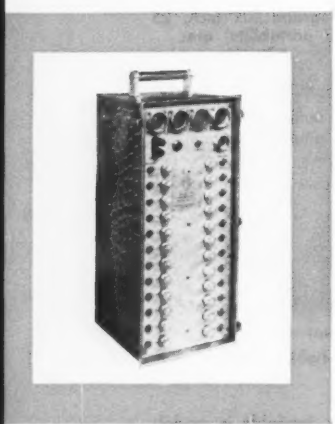
Damping ..... No load —50% critical.
300 ohm load—70% critical.

Impedance ..... 300 ohms output impedance at 30 cps.

Recommended Depth of Water..... Without Preamplifier —25 feet or more.
With Model 700 Preamplifier— 2 feet or more.

OPEN-CIRCUIT CONSTANT R.M.S. PRESSURE CURVE





MODEL 700 SERIES PREAMPLIFIER

12 Channel	24 Channel
18½" x 8½" x 5"	18½" x 8½" x 8"
22 Pounds	32 Pounds

Voltage Amplification .. 35.

Power Amplification.... 2,000.

Filtering ..... Approx. 6 db/octave cut beyond 30 cps to offset normal high frequency emphasis of seismic signals in shallow water.

Input Impedance..... Designed to accept one or more Model 321-MT 300 ohm pressure detectors.

Output Impedance ..... 180 ohms with level control at maximum.

Noise (Electrical)..... The noise developed with a 300 ohm resistive input (in a band width whose 50% points are 21 cps and 45 cps with a 24 db/octave low cut slope and a 12 db/octave high cut slope) is less than 0.04 microvolt r.m.s. referred to the input. This is approximately 12 db above thermal noise.

Sensitivity ..... Of Model 321-MT 300 ohm Detector and Model 700 Preamplifier is approximately 14 microvolts/dyne/cm^2.

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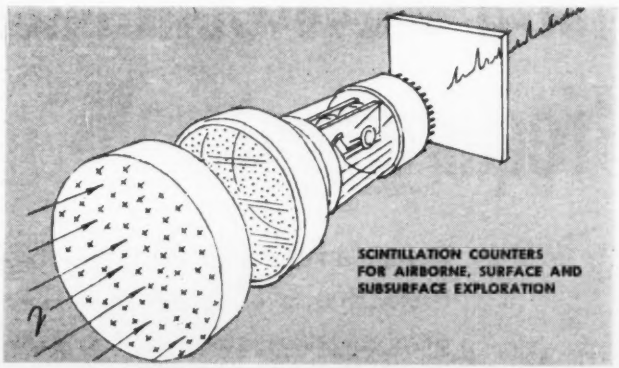

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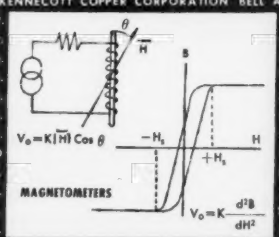

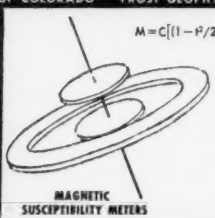

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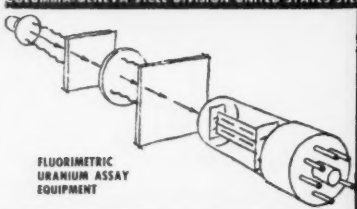

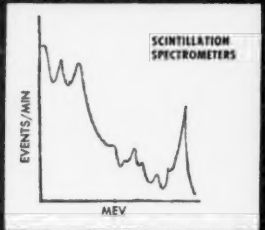

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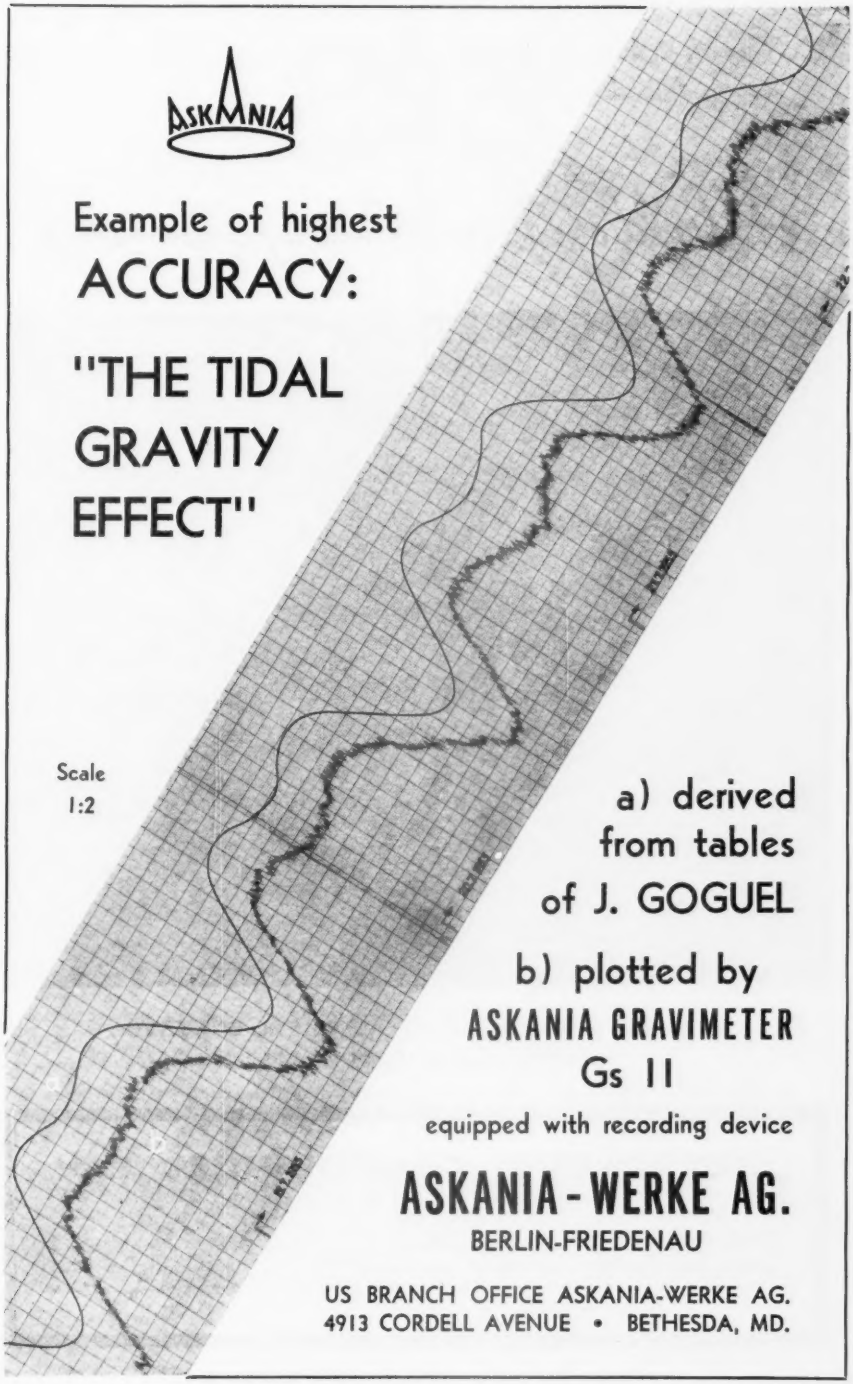

Scale
1:2

a) derived
from tables
of J. GOGUEL

b) plotted by
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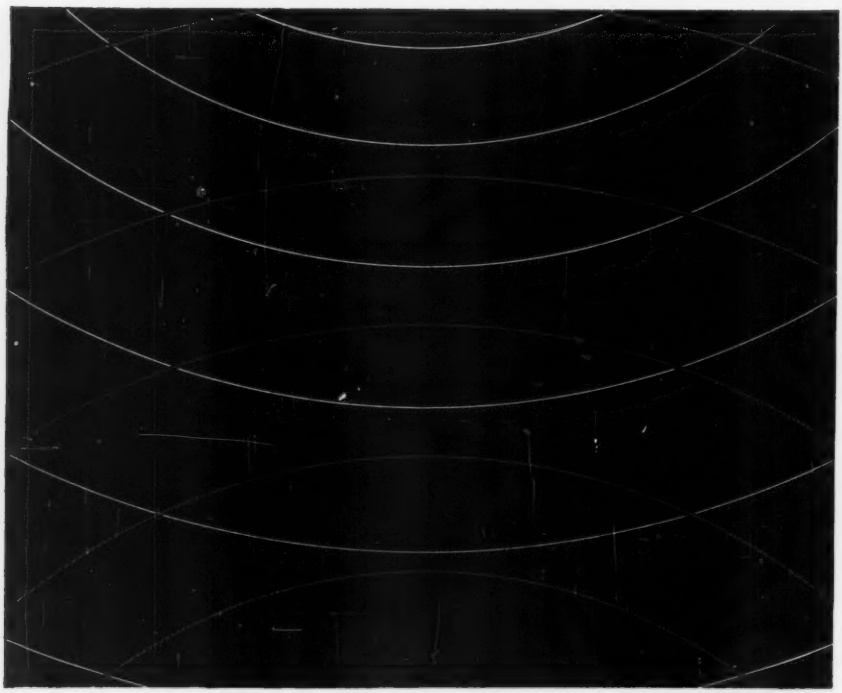

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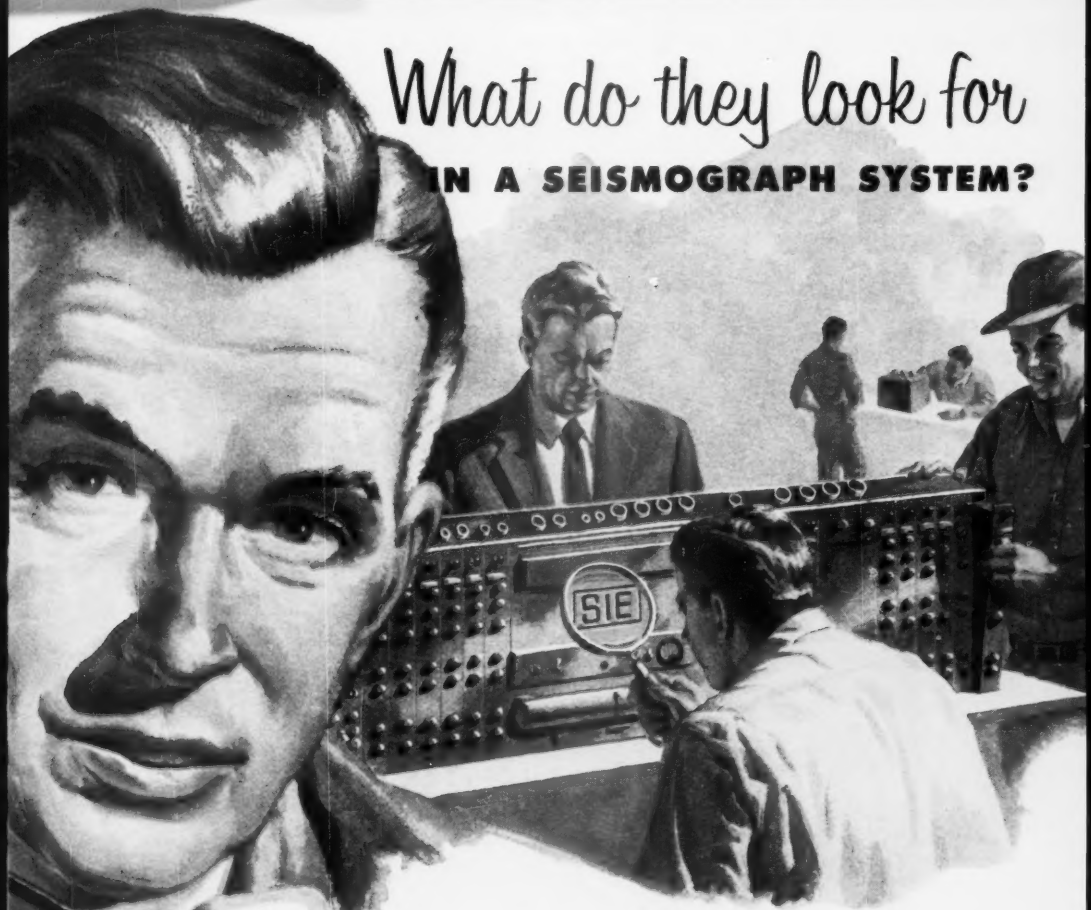

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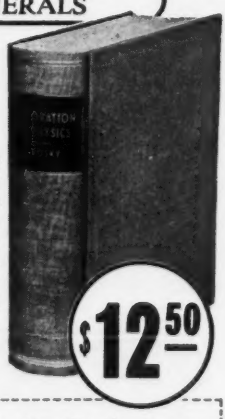

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